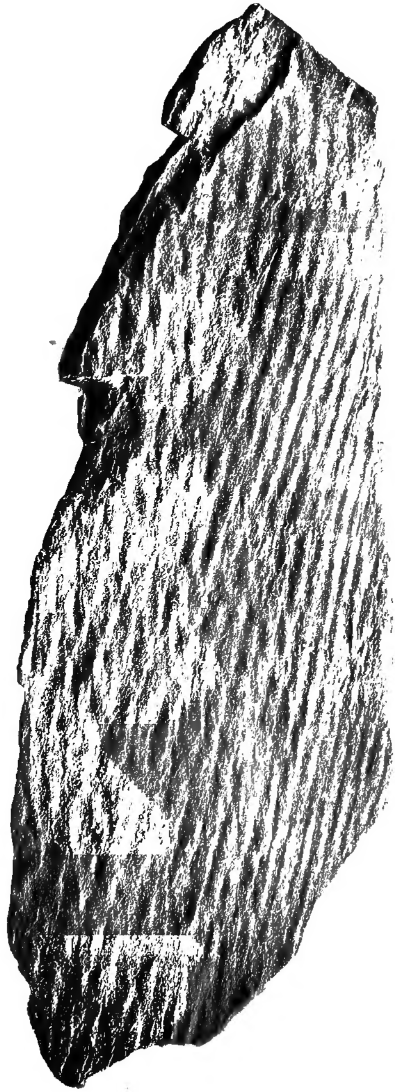
GEOLOGY OF

WORCESTER, MASSACHUSETTS



LEPIDODENDRON ACUMINATUM (LESQUEREUX). ONE-THIRD NATURAL SIZE. FOUND AT WORCESTER "COAL" MINE, 1883. PHOTOGRAPH BY JOHN M. BLAKE.

THE

GEOLOGY OF WORCESTER,

MASSACHUSETTS.

BY

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PREFATORY NOTE.

THE work of choosing the material to be presented in this work and of writing out the descriptions and preparing the illustrations, has fallen wholly to Mr. Perry, while the subscriber has gone over the work carefully, and helped in suggestion and revision.

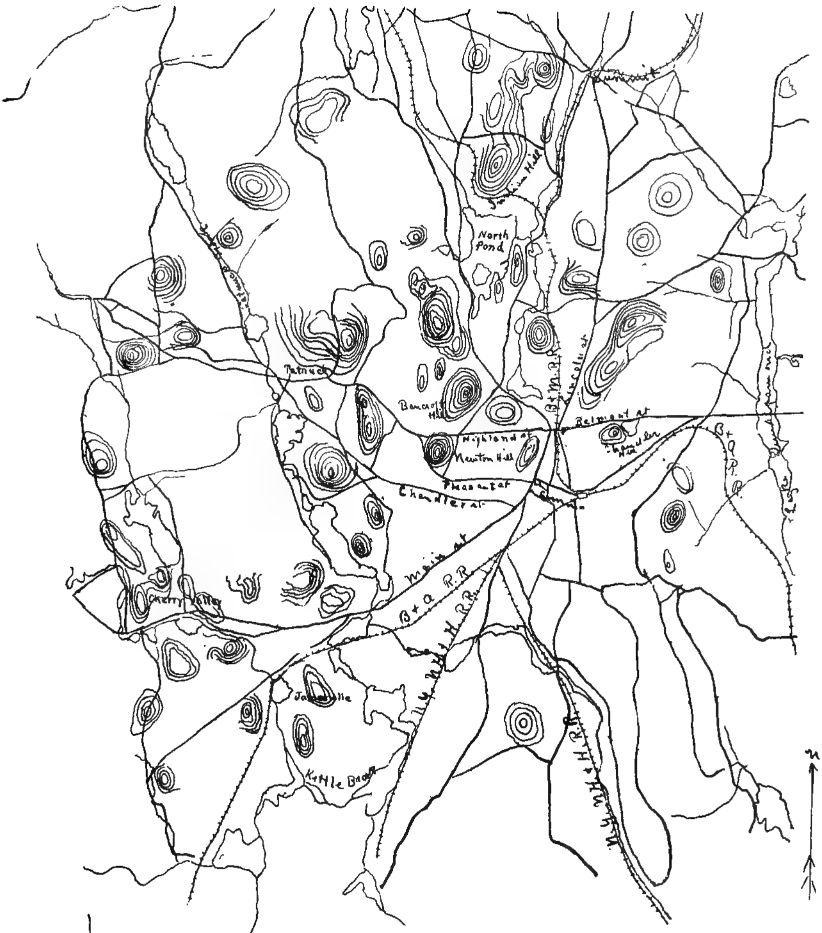
The writer has been engaged for several years in the mapping of the rocks of Worcester County for the U. S. Geological Survey, and Mr. Perry has assisted him in this work from its beginning. He has come thus to have a very full knowledge of the geology of the county and especially of the region about Worcester. The work thus incorporates much work that has been done under the authority of the U. S. Geological Survey, and is published in this form by permission of the Director.

B. K. EMERSON.

PREFACE.

This book has not been written for geologists. It has been written for the people of Worcester; for those who have no technical knowledge of the subject of geology, and in such a style, we hope, that, taken in the hand, it will serve as a guide over the fields and through the streets in the study of the rocks of Worcester, and of their relations to one another. But while the book is written for the amateur in nature study, rather than for the professional geologist, we have not tried to slide over or omit the problems here presented, but to solve them in untechnical language.

To the people of Worcester, then, we dedicate this book, hoping that it may be a source of pleasure and profit in their walks about the city.



MAP OF DRUMLINS OF WORCESTER.
MADE FROM TOPOGRAPHIC MAP OF U. S. GEOLOGICAL SURVEY.

INTRODUCTION.

In the "Physical Geography of Worcester" it has been pointed out that beneath all of the loose rock material constituting the larger part of the earth's surface about us, there is a rock-floor; that this loose material covering this rock-floor is of varying thickness—frequently not more than twenty-five feet deep, but in the drumlins it reaches a thickness of 150 to 250 feet, and in the sands and gravels, partially filling the old brook and river valleys, it is 100 to 200 feet in depth; that, here and there, parts of this rock-floor appear at the surface, and these parts are called outcrops or, in common language, ledges. Whenever we see a ledge, we are to think of it as a visible part of this rock-floor extending in all directions around beneath this thin coating of loose material. Whenever the workman, in digging the sewer trench, reaches ledge, he has simply excavated down to the underlying rock-floor. The elevations and depressions in this rock-floor, within Worcester, agree only in a very general way with the elevations and depressions of the visible surface of the earth. This is especially due to the abundance of drumlins in the western part of Worcester; and, as these are a part of the covering, we must annihilate these in thought while we think of the rock-floor. To make this easy the accompanying map has been added showing just which of our hills are drumlins.

If then we wish to study this rock-floor, we must study it as it is revealed in its outcrops or ledges, both at the surface and in excavations made by workmen.

GEOLOGY OF WORCESTER.

CHAPTER I.

Worcester Phyllite and Mica Schist.

To one who has not studied the ledges in any systematic way, but has only casually observed them here and there, while riding or walking about the city, they may seem to be distributed in the most confused manner. While there is quite a remarkable variety for so small an area, the ledges are arranged in a well defined order which clearly appears when we study them systematically, and fix their positions on the map. It makes little difference where we commence in our study of the rock-floor as it appears in the outcropping ledges, for everywhere there is order. Let us, then, begin at a point as near as possible to the Natural History Society's building. When the workmen excavated the cellar of the new courthouse on Court Hill, they cut into the underlying ledges, and revealed the rock-floor for our study. The rock is of a slaty drab color; has a noticeably smooth, greasy feel; is irregularly laminated, and hence, because of the cleavage between the laminae, tends to break in flaky fragments, a mass of these looking like a pile of slaty chips. The laminae of this rock are very thin—only a small fraction of an inch in thickness—and are roughly parallel, and irregularly curved; hence the unevenness of the surface when the laminae are separated as they are when the coarse irregular flakes are chipped off. While the rock breaks quite easily between the laminae because of its cleavage, at right angles to them it is quite hard and resisting. On the surface of the laminae there is a faint lustre or glimmer, except where weathering has taken place, producing a coating of iron rust. Such a rock as this is now called phyllite. It was formerly called an argillite, but this name implied the presence of clay in the rock. The original mud rock or shale, out of which it was formed, has been recrystallized into a mat of minute mica scales and quartz grains. When the rock becomes so coarsely

Rock in Court House Hill.

crystalline that the mica scales are clearly visible, it is called a mica schist. Such is the rock-floor here. With this general description in our minds, let us extend our observations. Some years ago, while workmen were digging a trench through Lincoln street, all the way up the hill they found rock of this same description; at Adams square there are numerous outcrops or ledges of the same; at the Summit station of the Boston and Maine railroad is a deep cut through the same kind of rock. We may conclude, with a reasonable degree of certainty, that the underlying rock-floor between these points is made up of like rock.

Rock in Elm and Pleasant streets, Oread Hill and Woodland street.

If, on the other hand, we extend our observations to the south, we find that the same rock appeared as workmen dug the sewer trench in Elm street near Fruit, and in Pleasant near Merrick and Russell streets; it also appears in large outcrops in Oread Hill, and in various places in Woodland street to Clark University. On passing to the eastern part of the city, and starting, in our observations, at the deep cut where the Boston and Albany railroad passes under Plantation street, we find this same phyllite exposed to a depth of twenty-five feet and for a distance of a third of a mile or so. Thence we may follow this rock, in numerous outcrops, south through Plantation street over Oak Hill, and thence over Providence-street and Vernon-street hills, across the Blackstone to Pakachoag Hill and thence into Auburn. Reasoning as we did in the case of Court Hill, Lincoln street and Summit areas, we conclude that, under the covering of loose material consisting of sand, gravel, clay and the like, this phyllite extends, connecting these separated areas. That we make no mistake in this conclusion is shown by numerous borings and cuttings which have revealed the surface of the rock-floor between some of these localities. By just such work and reasoning has the accompanying geological map been made out, showing that part of Worcester under which this phyllite extends, constituting the rock-floor. It is the area marked blue.

Extent of the phyllite.

From this we see that the area, within which this rock is found, extends across Worcester in a north-south direction, varies in width, and is quite irregular in outline. But this study has not been confined to Worcester. In like manner this rock may be traced far to the south, where it becomes a mica schist, through Auburn, Oxford, Dudley, thence into Connecticut through Woodstock and Pomfret; and there, about

Railroad Cut Near Bloomingdale.

a mile north of Wolf Den Hill, famous because of Gen. Israel Putnam's undaunted courage, this rock comes to an end. Through this extent it narrows, until it is not more than 200–300 feet wide at its southern end.

In like manner it has been traced to the north where it broadens through Boylston, West Boylston, Sterling, Lancaster and other towns still farther to the north.

Study of the rock at the deep cut of the B. & A. R. R.

Having thus seen, in a general way, somewhat of the extent of this rock underlying Worcester, let us attempt to obtain a clearer idea of it from a more careful study at some of its typical localities. There is no locality where the rock may be studied to better advantage than at the deep cut through which the Boston and Albany railroad passes under Plantation street. Here, for about a third of a mile, a cutting has been made through the solid rock-floor to the depth of twenty-five feet or more.

As we look at the solid rock on either side, we notice a certain regularity of structure. The rock material is arranged in thin sheets. This becomes even more evident, if we break a piece from the vertical wall. Under the blow of the hammer, where the rock is somewhat weathered, it may break into a mass of thin sheets or laminae; or if we look at a surface at right angles to the sheets, we may see, in the thickness of only an inch, so many laminae that we can with difficulty count them. Moreover these sheets or laminae have a certain parallelism in position, standing up at a high angle from a horizontal position and pointing in a northerly direction. To be more accurate we determine this direction in several places, by means of the compass, remembering that the magnetic needle here points about twelve degrees west of the true north, and find the direction in which the laminae point, to be generally between twenty and thirty degrees east of north. This is called the strike of this rock; and the strike of rocks will frequently be taken in our study, for it will reveal to us many facts that would not otherwise be observed. We also notice that the laminae slant down towards the west. We measure the angle which they make with a horizontal plane, and find this to be, generally, about eighty degrees. This is called the dip of the rock; and because the slant is towards the west, we say that the dip is to the west. This, also, we must carefully note in our observations, if we would comprehend aright the facts presented to us.

Looking at the surface presented when the rock breaks between the laminae, we see that the rock is of a light slaty color. It glistens brightly in the sunlight. This glistening is due to an infinite number of bright points, each one of which, under the magnifying glass, is seen to be a little mica scale. The surface is a mat or felt of these scales, each parallel in position with its neighbors. It is because of this parallelism that the rock material is arranged in laminae, and breaks into these thin sheets. It breaks more easily between the scales than it does across them. The color of the ledge varies considerably. Seen from the car window, one might think the whole ledge to be of a very dark, dull, dirty grey color; but in reality there are many shades of red and brownish yellow, of dark brown and grey, all more or less modified by the accumulation of smoke and cinders from the engines.

Detailed study of the rocks of the cut from east to west.

But if we give only this casual examination to the rocks here, they all appear much the same. In reality they are quite variable. Let us therefore examine the ledge carefully, and every few feet break off fragments for examination. Commencing at the east end of the cut, we break a fragment from the ledge, where it just appears above the ground. It is a fissile, crinkled phyllite of a dark slate-drab color, much darker than is the average, and of a greasy feel. Drawn across the page, it leaves a mark like that left by the lead pencil. We immediately know that this contains graphite, the substance contained in the pencil. To this graphite is due in part, at least, the smooth greasy feel. This feel is in part also due to the decomposed mica of the phyllite. Such hydrated mica is often called sericite, and the rock a sericite schist. Here may also be noticed masses of white, granular, glassy quartz which are parts of quartz veins. In this rock, at some time, fissures or cracks were formed, and these were filled by quartz that was brought in and deposited by water.

Then passing along a few steps to the west, we again break off a fragment. Here the rock is lighter in color, because of the absence of the graphite, and somewhat sandy in appearance, from the larger quantity of granular quartz in it. But this quartzose band is narrow, and then we again find the normal phyllite.

Andalusite phyllite.

At about forty feet from the east end on the north side of the track, on breaking into the ledge, we notice a peculiar irregularity of the surface of the

Mica Schist, Showing Irregularities of Surface Due to Contained Andalusites. Original, 5 Inches by 4. From Railroad Cut, Near Bloomingdale.

laminae. The surface looks very much as the surface of one's hand looks when a sliver has been forced in beneath the skin, only here the apparent slivers are very abundant. These slivers lie in the plane of the laminae, and the laminae may be seen at the edges wrapping around them. At the edges also we are able to see just what the slivers really are. They are little glassy prisms whose ends are frequently, in part, covered by a brassy coating. These sliver-like prisms, giving to the rock this peculiar appearance, are probably crystals of andalusite, a mineral frequently found in this rock in other places. The brassy mineral is iron pyrites, which is also frequently seen in this rock. This latter mineral occurs generally not in large masses, but as a thin coating between laminae, and on the surfaces of fine fissures, even making up fine streaks or bands.

For a hundred feet or so the phyllite continues to contain these sliver-like andalusite crystals, sometimes more abundantly and at times less so. The rock then becomes the normal light grey, thinly fissile, smooth, soft phyllite.

Development of a secondary structure.

After continuing our study in this normal phyllite a short distance, when we are about two hundred feet from the bridge, we observe an unusual appearance on the surface of the ledge. There are quite regular lines, approximately parallel and horizontal, crossing the face of the ledge. These lines are sometimes an inch apart, sometimes two or even three; and above these lines the rock frequently projects a little, as if some of the rock just below the line had fallen away. This gives to the surface an unusually ragged, angular appearance. Examining this appearance more carefully we find that it has a deeper meaning than at first appears. The lines are cracks or fissures cutting across and through the laminae, not between them, as if some one with a thin, sharp knife blade had cut through the laminae as he might cut through so many sheets of paper. On still more careful examination we see that the cutting was not done so nicely as we at first thought. Each little lamina, or, better, several of these laminae are, as it were, stuck together and bent so that their edges together present a figure having this shape,

and the laminae between two adjacent fissures are arranged in a succession of these figures.

In other words the upper part of each lamina is bent towards the left, and the lower part towards the right. This clearly indicates a motion between these different sections by which the upper and

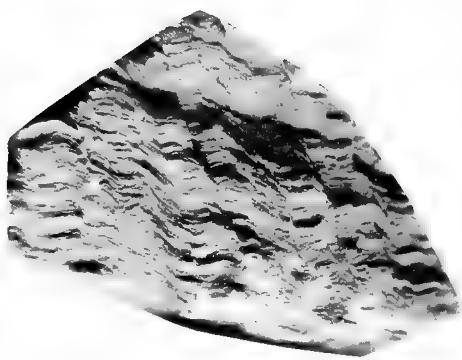
lower edges of the laminae in a section are bent in opposite directions. Either each section above moved more to the left than did the one beneath, or each section beneath moved more to the right than did the one above. Possibly this structure may result from simple pressure at right angles to the planes between these sections, by which a yielding at right angles took place, and thus the laminae have come to have an undulating form.

This structure is interesting as the beginning of a remarkable change. Let us think of the upper edges of these laminae bent a little more to the left, and the lower edges a little more to the right; then again the upper edges still more to the left, and the lower still more to the right; it is evident that the laminae will approach more and more nearly to a horizontal position until they practically reach it, and the laminae of one unit overlap and underlap the laminae of the adjacent units to the right and left. When this change is complete the segments of the laminae will be horizontal where now they are vertical. This is a clear illustration of how the laminae of a rock may be rotated, even to a position at right angles to their former position, and thus the capacity of splitting in one direction obliterated and replaced by a capacity of splitting in a new direction. This may be called the development of a secondary or slaty cleavage.

From these observations on cleavage, we continue our study, still going to the west. Nothing new attracts our attention until we are within a hundred feet of the bridge. Here the phyllite is again noticeably dark in color, with the smooth, greasy feel characteristic of graphite. It is another graphitic band in the phyllite, and bands like this are not infrequently met with in other parts of this rock. But this graphitic band is only a few feet in width, and then again the rock is the normal phyllite until we reach the bridge.

Micaceous quartzite.

On the west side of the bridge we immediately notice a marked difference in the appearance of the rock. It is apparently much more massive; but the fissile structure appears when we break a fragment from the ledge. The ledge is cut by clearly defined joints into blocks of remarkable regularity. This rock proves to be quite different from the normal phyllite. While the material of it is arranged in thin laminae, the rock is much harder, and the laminae are more regular and more clearly defined. Under the magnifying glass it is seen to



Development of a Secondary Structure by the Rotation of the Laminae in Sections.

be made up of bands of light grey, finely granular quartz, alternating with bands of a brownish grey color, also consisting largely of finely granular quartz. These bands are separated by thin, darker sheets of dark brownish mica in fine scales. These bands are generally as clearly defined as are the bands in an agate, and are at times not more than one eighth, one sixteenth, or even one thirty second of an inch in thickness. While these bands are generally regular and extend parallel with the general lamination of the rock, now and then one or more is crumpled into fine, closely compressed folds, while the adjacent bands are but slightly disturbed. In this are also found bands containing flattened cylinders of light grey, slightly reddish, granular quartz inclosed by micaceous folia folding closely about them. Farther along these flattened cylinders have been so flattened, as it were rolled out, as to be almost paper thin; and then, sometimes, they are folded into almost innumerable compressed folds, giving to the rock a coarsely ribbed appearance on the lamination surfaces. This rock, because of the abundance of quartz in it, may be called a micaceous quartzite. This continues to be the rock, on either side of the tracks, for about two hundred and fifty feet from the bridge; then the quartzite alternates with thin bands of the phyllite for one hundred or one hundred and twenty-five feet, and then the rock becomes the pure phyllite, practically the same as that found on the east side of the bridge.

Dike of aplite in micaceous quartzite.

While making this study of the quartzite, breaking off fragments constantly, we find quite a different rock in the midst of the quartzite on the north side. It is white, or nearly so, in color, in strong contrast with the bordering rock. It is possible to draw a line clearly marking the boundary of the white rock. It is also divided in two parts by a thin layer of the micaceous quartzite. The whole thickness of the white rock is fifteen feet. On closer examination this rock is seen to be finely granular in texture, yet divided into folia as thin, and almost as regular, as those of the bordering quartzite. In the finely grained white mass we may distinguish two minerals—the clear glassy quartz which, now and then, appears in rounded particles many times the size of the surrounding grains, and the white porcelain-like, finely granular feldspar. These make up, practically, the whole of the rock. In addition there may be found, here and there, a little pink garnet. Covering the surfaces of

the folia, and seen only when the rock is broken between the folia, are minute scales of muscovite or sericite mica. In spite of the foliation parallel to the lamination of the neighboring rock, we recognize this rock as a foreigner, not really belonging with the adjacent rocks. It came here in a molten state, flowing into the fissure which it now occupies, and there solidified, forming a dike of aplite, a variety of granite. By subsequent pressure and crushing, the separate minerals were reduced almost to powder, and the muscovite scales were developed on surfaces which rubbed against each other, thus giving to the rock its thinly foliated structure.

Weathering of the rock of the cut.

From this aplite dike we continue our study of the facts here presented. We notice quite frequently that there is a narrow part or band of the ledge which is largely concealed by a steeply sloping bank of loose rock material. In one case this bank may reach but a few feet up against the ledge; in another case, far up so as to conceal the rock almost to the top. On examining this fine material, we find it to consist largely of fine scales, evidently derived from that part of the ledge which it conceals. On climbing up one of these banks so as to reach the ledge above, we find the surface of the ledge made up of loosened, scaly particles ready to fall and to be added to the bank of *débris*. This is an admirable illustration of the way in which such rock breaks up and crumbles under the action of atmospheric agents. This process is called weathering.

This weathering or decay is partly mechanical and partly chemical. In the first place the nearly vertical wall of rock on either side is made up of many uneven surfaces, and contains innumerable nooks and crannies. The ledge, on account of these irregularities, presents a large surface for action, and affords convenient lodgement for water, snow and vegetation. The many joints, cutting the ledge in different directions, afford innumerable paths by which the water may enter and soak through the rock. The many little streams, dripping from the walls of this ledge, even during the dryest of seasons, show very plainly that the water finds these capillary channels, and makes use of them. Then the frequent jar from passing trains serves to open the joints near the surface, and loosen the blocks, and finally throw them down the talus. The texture of the rock also favors the action of weathering agents. Water soaks in between the thin laminae. The soaking waters act in a twofold way. During the cold months,

the water between the laminae, or in joints, or cracks, or crevices of any kind, freezes and expands, and thus enlarges these spaces, and breaks the rock into pieces. In this way many blocks are loosened and thrown from the ledge. The laminae are forced apart and weakened, and are ready to crumble.

During the warm months of the year, and within the ledge where frost cannot reach, the water works in another, yet effective, way. Dissolving carbonic acid and oxygen from the air, sulphur dioxide from the smoke of the passing engines, and acids from the decaying vegetation, the water carries these into the rock to act upon and disintegrate the mineral constituents, and thus weaken and break up the rock. But as the water carries in material, it likewise brings out products of change and decay. The lower surfaces of the overhanging rock are frequently covered by an incrustation left by the evaporating waters. The incrusting substances were formed in the rock, dissolved in water, brought out to the surface, and there deposited as an incrustation by the evaporation of the water. The thick coating of iron rust, covering the beds of the brooks by the side of the tracks, is further evidence of change within the rock. That iron was, formerly, all in the neighboring ledge.

By these changes, partly mechanical and partly chemical, this rock surface is being disintegrated and reduced to fine material, but not uniformly. For one reason or another one band is acted on much more rapidly than the adjacent bands are, and there is produced a recess in the wall and a high, sloping talus of fine *débris*.

Having noticed these interesting facts, we continue our study of the rock as a whole, continuing to break off fragments frequently for examination. We constantly find the light grey phyllite, having finely crinkled surfaces, and breaking into thin laminae whenever struck by the hammer.

Hornblende rock. A basic eruptive in the cut.

When we are about seven hundred feet west of the bridge, the rock suddenly changes. It is massive; on the weathered surface it is of a light rusty color; but, within, of a dark greenish grey. Through the magnifying glass, we see that this color is due to a fibrous, or bladed, dark green mineral, which is frequently arranged in radiating masses, one half inch or more in diameter. This mineral we recognize as hornblende, and the rock is a massive hornblende schist.

But there is not, so far as we can see, any connection between this rock and the neighboring phyllite, in which it forms a band two to three feet wide. It is in the phyllite, but not of it. At some time, in the changes, which the phyllite has been through, of folding, of elevation and depression, of crushing and breaking, a fissure was formed, where now we see the hornblende schist, and into this fissure flowed some basic, molten rock which solidified there, making a dike. By subsequent chemical and mechanical changes in the rock of this dike, it has been transformed into this massive, hornblende schist.

Glacial striae on the surface of the ledge.

We then continue our study to the end of the cut, four hundred and twenty-five feet or so from the hornblende schist, but find only the normal phyllite. If, however, we go up on to the surface of the ledges, on the south side of the tracks, we may see something of interest to us. In a number of places the surface of the ledge is covered with grooves and scratches parallel to one another; aside from these the rock surface appears smooth, almost polished. By means of the compass we take the direction of these, and find them pointing five degrees east of south. These are some of the glacial scratches so frequently found on the surfaces of the ledges about Worcester, and show us the direction in which the ice of the Glacial Period moved over this region.

We have thus pointed out different facts that may be observed in passing through this railroad cut; but before we seek for the general interpretation of these, it will be well for us to gather facts from another typical locality.

Observations in Plantation street on the way to the "Coal Mine."

Let us leave the electric car at the corner of Plantation and Belmont streets, and go to the north through the former street. We may notice, now and then, by the side of the street small outcrops of the phyllite like that just studied at the railroad cut. Then all trace of this rock disappears; and, crossing the first small brook, we find in the field, just over the wall, on the left, a ledge of rock closely resembling the micaceous quartzite just west of the bridge in the railroad cut. It is a micaceous, sandy, granular quartzite. Just beyond, in the gutter, by the side of the road, the surface of the ledge is smooth and covered with scratches which we recognize as glacial scratches. Taking the direction of these, we find them pointing thirty degrees to the east of south. Com-

Worcester "Coal" Mine. Mouth of the Old Shaft is at the Foot of the Cliff in the Foreground.

paring this observation with that made at the railroad cut, we note quite a variation. This is due to some local cause in this last locality, as we do not generally find these marks pointing so far to the east of south. We also take the direction of the laminae here, and find them pointing or striking thirty-two degrees east of north, and dipping eighty degrees to the west. If we follow this direction back to the south, we find that these beds point back to the micaceous quartzite of the railroad cut. There is every indication, then, that these different outcrops belong to one and the same rock, while the phyllite, that was east and west in the railroad cut, does not appear. A glance at the geological map will make this clear.

Granite porphyry in bowlders by the roadside.

As we proceed in this study our eyes must constantly be on the watch for facts. A stone wall may often afford the solution of some difficulty, or it may furnish us an index of the rocks found in the area around, where the ledges may be completely concealed. And so, as we walk along, we look at the rocks in the stone wall and in the gutters by the roadside. Soon a rock attracts our attention because of its peculiar appearance. It resembles the granite of the neighboring hill, to the west, in color, but is quite different in texture. It is a light colored, massive rock, the larger part of which is finely granular in texture, and more or less rusty in color. In the midst of this finely granular mass are distributed crystals of orthoclase feldspar, known by their bright, shining surfaces, which flash as the specimen is turned in the sunlight. These surfaces are generally longer than they are wide, and sometimes show the sharp angles of definite crystals. In the granular mass are distributed particles of quartz, distinguished from the feldspar particles by their glassy appearance and want of cleavage surfaces. These quartz particles are generally slightly rusty, and darker in color than are the other minerals. Examining one after another of these particles under the magnifying glass, we notice a certain regularity of shape in one. It may be well for us also to examine the cavities left by some of these particles as the rock broke under the hammer. We finally see a quartz particle having a definite, regular shape. It is a six-sided pyramid. We may possibly be fortunate enough to find a particle showing a six-sided pyramid at either end. The quartz in this rock is, now and then, in the form of a regular crystal, a double, six-sided pyramid. A specimen of this rock, rough and uninterest-

ing as it may at first seem, should be preserved, for it is an uncommon rock here in Worcester. The abundance of the fragments in the walls indicates that it occurs in the ledge in this immediate vicinity. So far as is known, the part of the rock-floor consisting of this rock is entirely covered by the glacial material. Because of the crystals imbedded in the finely granular mass, this rock may be called a granite porphyry. It is probably closely related to the granite of Millstone Hill, of which more will be said later on.

Approaching the "Coal Mine."

But we must not forget that we are on our way to the coal mine, located on the Swan Farm; and so, just west of the southern end of Wigwam Hill, we turn into the fields on the left. Here, also, the stone wall will reward our close observation. Bowlders may be seen here, consisting of layers which have been folded in an exceedingly complex manner. This folding is beautifully brought out by the weathering, which has given a reddish tint to some of the layers. Going to the west, we ascend the low hill and turn to the north. The stone wall tells us of a change in the ledge. The wall is now made up entirely of angular, flat, thin fragments of a light grey, finely grained quartzite, having many thin, white quartz veins, making almost a network through the rock. The abundance of these fragments leaves no doubt but that the ledge beneath is of the same kind. One thing is specially noticeable that, at some period in its history, this rock was shattered, producing innumerable little fissures, which were afterwards filled with quartz, constituting the quartz veins. These veins now stand out in relief because they are more resisting to the agents of the atmosphere than is the rock itself. Continuing to the north, along the crest of the slope, when almost directly west from the barn of the Swan Farm, we come to an overhanging cliff; beneath this is the mouth of the coal mine shaft.

Coal Mine.

This is a point of special geological interest, and it has been visited by many geologists. We cannot make too careful study here, for in this place is, in a certain sense, the key to the geology of Worcester. At various points around, the ledge appears at the surface. It is a very dark grey, almost black, phyllite or graphitic schist, presenting, on cleavage surfaces, a glimmering lustre. It generally breaks in thin, regular slabs, or in long, narrow, thin masses. It crocks the hands badly; and in a short time the hammer handle looks as if it had received a coating of stove-polish. On the cross-section the schist is of a dull black

color. We take the dip and strike, and find considerable variation. In some places the laminae point east and west, and in others some degrees north of east, but always far more to the east than in any other place where we have thus far made observations. This clearly indicates a decided warping or breaking in the laminae of the rocks between here and Wigwam Hill, just across Plantation street. The rocks of this area have evidently been subjected to great disturbances, by which they have been warped, folded, crumpled, even broken. This will become more evident as we proceed in our study.

Iron pyrites in rock at Coal Mine.

Let us now examine the rock of the cliff overhanging the mouth of the old mine. The laminae have a general slope or dip to the north or northwest. There is quite a variation in color. There are shades of yellow and brown mixed with light and dark grey, while here and there appear patches of green vegetation. These colors, excepting the green, are due to iron rust and other substances resulting from the oxidation of the iron pyrites which is distributed quite abundantly through the rock. This mineral is sometimes found here as a thin, light brassy coating between the laminae, and sometimes in thin veins and crystalline masses. It is oxidized by oxygen carried into the rock in solution in water, and forms either a sulphate of iron and sulphuric acid, or an acid sulphate. These in turn, especially when in solution, act on other minerals, and produce a variety of substances which appear on the surface of the cliff. From this source comes the yellowish coating of iron rust, appearing at the bottom of the pool beneath the cliff. But how does it happen that there is iron pyrites distributed through the rock? The rock is highly charged with carbonaceous material, which gives to it a black color. This carbonaceous material, or that from which this was formed, has acted as a reducing agent upon iron sulphate, taking oxygen from it, and has changed the sulphate into iron pyrites. This iron sulphate, in solution in water, was carried into the mud while the rock was forming, and the water percolated through the crevices and fissures, and soaked into capillary spaces, and there the change from sulphate to iron pyrites took place.

Graphite at the Coal Mine.

Let us now break into the rock of the cliff. It is all a dark grey or black carbonaceous schist or phyllite like that of the adjacent outcrops; but as the laminae slant up to the southwest, lower beds appear in

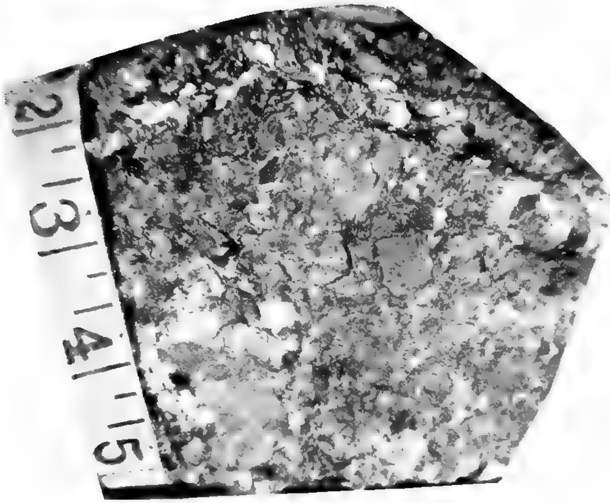
that direction, and these may best be studied at the western end of the cliff. Beneath the upper black schist is the bed of coal, or, better, graphite, which is probably the bed that was once mined, as this bed slopes down so as to pass beneath the overhanging cliff where is now the mouth of the shaft. This bed is some five or six feet thick, somewhat thicker than was the bed formerly mined, as it is described by Dr. Hitchcock and others. Where the hammer strikes, the substance of the rock appears of a dark grey color, with metallic lustre, and soft, smooth, greasy feel. This substance has the characteristics of graphite. But to be more careful before drawing our conclusions, we break off some fragments. The rock substance in part consists of white glassy quartz, more or less granular, distributed irregularly through the mass, while the greater part is of thin scaly or flaky particles, the larger ones a half to three fourths of an inch broad and long, arranged generally parallel to the lamination. These flakes have the dark grey color, metallic lustre, smooth greasy feel of graphite, and crock the hands and other objects, giving to them a coating having the same characteristics. Here also our hammer handle, in a short time, appears as if it had been covered with a substantial coat of stove-polish. This substance certainly has the outward properties of graphite, but as there has been some question whether it is really graphite, or a variety of anthracite coal, it was subjected to the final test. If we can prepare graphitic acid from it, we may conclude that it is graphite; if not, then we must conclude that it is only a variety of anthracite coal.

Graphitic acid from Coal Mine graphite.

Some of the material from the coal mine, in the form of a fine powder, was treated according to the directions for preparing graphitic acid from graphite; and, at the same time, powdered graphite from Ceylon was treated in the same way. From each there was obtained a yellowish colored substance agreeing in all respects with the description of graphitic acid. In fact it was easier to oxidize the coal-mine substance to graphitic acid than it was to oxidize the Ceylon graphite. From this we conclude that the substance at the coal mine is, in large part, graphite.

Graphite breccia.

To return to the specimens we were examining—we described the graphite as being in flakes. These flakes are bordered by irregular, angular edges, and are imbedded in finer material, also made up of finer, irregular, angular flakes



Graphite Breccia. Irregular Dark Patches are Graphite Flakes.

not parallel to each other. This structure becomes more clear in more impure specimens, where the angular flakes and their bedding are very evident. Mixed with these is a considerable quantity of glassy quartz between the flakes. From this study it is evident that this graphite bed is simply a mass of angular, flaky fragments. But if the graphite is now in this condition, it must, at some period in its history, have been completely shattered, and this period must have been since the carbonaceous material became graphite; and then these fragments must have been pressed together and quartz deposited between them so as to bring this substance into its present condition. This graphite bed has all the characteristics of a graphite breccia.

Graphite phyllite beneath the graphite breccia.

Under the graphite breccia band is a band or layer of hard phyllite of a black color, and abounding in graphite. This band has an irregularly broken, laminated structure due to the fact that the material of the rock is not arranged in regular laminae, but in flattened, irregular, lengthened lenses varying in size. Many are from five to seven inches in length, by three to four inches wide, by an inch and a half thick. These are so placed in the ledge that their longest diameters are parallel, and when the surface of the ledge is at right angles to these, the face of the ledge consists of the sharp ends of these lenses, giving a ragged, hackly surface. The surface of each irregular lens is shining, smooth, and striated, presenting the appearance that is called slickensides, and shows the lustre and color of graphite; while the interior is of a dull black color. Just how much of the substance of these is graphite is difficult to say, but judging from appearance a considerable part must be. However, other fragments when heated and then boiled with hydrochloric acid, lose most of the black powder, so part of it must be still coal. This material gives evidence of the same shattering that was noticed in the graphite layer, but the fragments are coarser, and they give evidence of a crunching of the rock by some outside force, by which they have become rounded and flattened, and their surfaces polished and striated from rubbing one against another. The meaning of all this will appear in another connection.

Fibrous prochlorite.

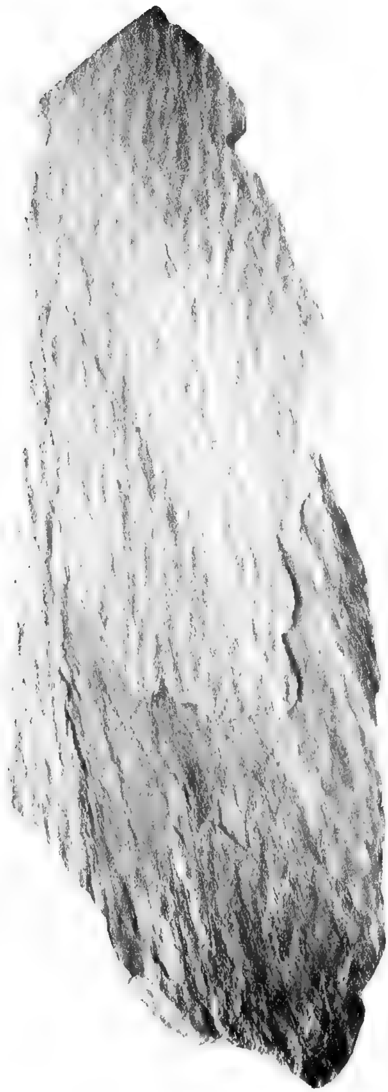
But there is here still more of interest for us. On breaking into the ledge overhanging the mine, we, now and then, notice some very fine fibres in layers or small masses. The same appears in the other outcrops near by. These fibres

sometimes occur in seams or veins an inch or two in thickness, the fibres running across from side to side of the vein. This mineral also occurs as a very thin coating, mingled with glassy, fibrous quartz, on striated slickensides, and also in irregular masses within the graphite breccia. This mineral is of a light green color, when not decomposed, but is frequently of a rusty tint because some of the iron in it has rusted out. The mineral is also characterized by a beautiful silky lustre. It is not strange that this mineral has been called asbestos, so closely does it resemble that mineral, but it has not the composition of the asbestos of the amphibole group, nor that of chrysotile, the fibrous serpentine. It was analyzed by Mr. L. G. Eakins in the laboratory of the U. S. Geological Survey at Washington, and its composition shows that it is a fibrous form of prochlorite.

Fossils at the Coal Mine.

On one of his visits to Worcester, Louis Agassiz was taken to this coal mine, as a point of special geological interest. "Where are the fossils?" he asked. On being informed that none had ever been found, he stated that they were there and would be found, if only careful search were made. On the 6th day of August, 1883, the first fossil plant was found.[1] The surface of one side of it is represented in the frontispiece, and the other surface is represented in the plate opposite. These represent the flattened trunk of a tree. Buried beneath many feet of earth, this tree-trunk was compressed or flattened so that now it is not cylindrical in shape. Again in the fall of 1899, another fossil, represented in the accompanying plate, was found, which, strange as it may seem, exactly fits that found sixteen years before, and is the cast of one surface of that tree-trunk, the cast of the other side having been obtained in 1883, with the trunk itself. Mr. Calvin H. Andrews, teacher in the South High School, states that he, while visiting the coal mine during his course at the Polytechnic Institute, also found a fossil plant. This, unfortunately, was lost. There can be no doubt but that fossils occur at this locality, in spite of the great change to which the rock has been subjected, and those who seek long and patiently may be rewarded. If, in breaking the rock at the coal mine, any strange or regular markings are observed, the specimens showing these should be carefully preserved because of their scientific value and interest. These fossils tell us an interesting story in regard to the origin of this graphite bed. The carbon of it was once

[1] "American Journal of Science," Vol. XXIX., 1885, p. 157.



Lepidodendron Acuminatum (Lesquereux). One-third Natural Size. Reverse Side of Fossil Shown in Frontispiece. Found at Worcester "Coal" Mine, 1883. Photograph by John M. Blake.

LEPIDODENDRON ACUMINATUM. ONE-THIRD NATURAL SIZE. FOUND AT WORCESTER "COAL" MINE, 1899. PHOTOGRAPH BY E. B. LUCE.

in vegetable substances of plants and trees growing upon the earth; these substances became imbedded in mud, and were transformed probably first into peat, then to coal, and last, in large part, into graphite.

Former state of the phyllite.

But this graphite bed with its fossils tells us more. As it occurs in the phyllite, it tells us that this rock has not always been as it now is. It tells us that the rock has been made out of that material in which vegetable matter would most likely be buried—mud or beds of clay. And what is true of the phyllite at the coal mine, is also true of that at the railroad cut, already studied, for the latter contains graphitic bands. In other parts of this phyllite, both in Worcester and in other towns, are found bands more or less graphitic, so that in spite of the slight variations in outward appearance and crystallization and minerals contained, we may conclude that the phyllite was once in the form of beds of mud or clay, and during a part of its history supported a luxuriant vegetation. The remains of these plants became buried in the mud of marshes, and have been transformed into the graphite of these graphitic bands.

Metamorphism in formation of the phyllite.

But we may justly ask by what change, and by what agents, beds of mud or clay have been transformed into this phyllite or fine mica schist. We may partly answer this question by studying specimens of phyllite from different localities. Some of these show but a glimmering surface, even under the magnifying glass; while others show small scales of mica as the essential part of the laminae; while all under the large microscope, are seen to be made up, in very large part, of mica scales and quartz grains. Further study shows that these mica scales were not deposited by water as a part of the mud, for they give no evidence of having been washed about and broken by contact with other particles. They have the appearance of having been formed in the rock where they are. But they are crystals, more or less nearly perfect, and constitute the great mass of the rock. The change, then, that has taken place must have been, in part at least, a crystallization of the former muds or clays. But a mere crystallization implies that the substances, before and after crystallization, are identical except in form. Not so, however, with the beds of unchanged mud or clay and the crystallized rock material formed from them. The former is not a single substance, but a mixture

of various substances that happen to be carried by currents of water and deposited because those currents are no longer able, for one reason or another, to carry the particles farther. In such deposits, in a region like this, will be the kaolin from the decayed feldspar of the granite; also the ground up feldspar which escaped decay, but has been reduced to powder by the wear to which the granite pebbles have been subjected in the brooks and rivers; and mica and very fine quartz, also from the neighboring crystalline rocks. With such a complex mixture as this, something more than mere crystallization must take place to transform these sediments into a rock in which one mineral predominates. There must take place a chemical action by which the elements of the old sediments are rearranged into the minerals of the schist. This is the change that has occurred in the beds of mud and clay, the elements in the substances of these have been rearranged into new substances, with possibly the exception of the very fine sand, and these substances, including the fine sand, have been crystallized into the crystalline particles and grains and definite crystals found in the phyllite and mica schist.

Agents of metamorphism.

Such being the change that the mud or clays have undergone in becoming this phyllite, we may ask what agents have taken part in this change, for this mixture might remain indefinitely under ordinary conditions without ever forming any new minerals, or the old ones ever becoming crystallized.

Pressure.

Pressure has undoubtedly been an element in this change. Much phyllite has been removed by erosion, so that what is now at the surface was once deeply buried beneath the overlying mass, and hence subjected to the pressure of that weight. Moreover, this rock has been tremendously compressed and folded and crumpled in an exceedingly complex manner. During this folding and compression the mixed sediments were subjected to great pressure resulting in motion between the particles, as well as in the motion of large masses. Pressure, especially when accompanied by motion, is sufficient to induce chemical action between substances capable of mutual action, especially when this action is accompanied by contraction, that is, when the new substances are more dense or occupy less space than the old substances did.

Heat.

But the folding and crumpling of strata must have produced friction. Stratum rubbed against stratum,

and particle against particle, and thus generated heat within the very rock substance. This heat of friction must have been more or less increased by heat from within the earth, the increase depending on the depth at which this rock material was beneath the surface. Possibly also the heat of this rock mass was increased by that derived from molten rock masses that rose from beneath into the midst of these sediments or near to them. Heat, also, of itself is capable of inducing chemical action, and would be sufficient to produce changes in these beds of clay, were other conditions normal.

Moisture. Moreover these sediments would, from the manner in which they were deposited and from their position, be moist. The solvent power of water is vastly increased by pressure and heat, so that it dissolves mineral substances not soluble under ordinary conditions. Substances in solution much more readily act chemically because of the greater ease of motion and closer contact. Thus we see that the moisture in these sediments helped in the formation of new substances out of the old.

Uniformity in position of mica scales and reason therefor. Under the conditions through which those beds of clay have passed, the various mineral substances were subjected to the combined influence of these various agents of change, and being capable of acting on each other, formed new substances. The new substance formed in greatest abundance was mica. But as mica forms, it tends to assume the shape of little, thin, scale-like crystals. These little scales, more or less nearly perfect crystals, as formed, assumed a certain parallelism in their position, giving the cleavage that is so marked in the schist. It is reasonable, then, that we should ask why these mica scales so arranged themselves as this new substance was formed. Let us think of a rock mass subjected to pressure from all directions, and the pressure from one direction equal to that from every other direction. The simple result of such pressure would be compression, the particles being forced nearer and nearer together. This pressure from all directions may be resolved into three pressures, at right angles to each other—an up and down pressure, an east and west pressure, and a north and south pressure. Now let us think of unequal pressures—one greater than either of the other two, and these other two equal. Let us also think of the greater pressure exceeding the others by more than the strength of the rock under consideration. Let a rock mass then be subjected to these three pressures at right angles to

each other. Now, instead of simple compression, as when the pressures were equal, there will be a yielding in the plane of the smaller pressures, and at right angles to the larger pressure. Let us now think of mica scales being built up in this yielding mass. They will be built up in the direction of the yielding,—not against the greater pressure, but in the direction of the smaller pressure. As a result of this arrangement, the mica scales lie in the plane of the smaller pressures and at right angles to the greater pressure. As a result of this arrangement of the mica scales there will be a rock or slaty cleavage. Other minerals like chiastolite and staurolite, formed at the same time and capable of growing in one or two directions more easily than in the third, also arrange themselves in the plane of less pressure; while other minerals, like garnet, only capable of growing in all directions with equal ease, are not affected by the greater pressure and are found imbedded in the schist without order or special arrangement. The cleavage and the arrangement of the mica scales, and of other minerals within the phyllite, are due, then, to the greater pressure that was exerted in one direction during the crystallization of these minerals. As the mineral matter of the rock was undergoing this change and crystallization, the beds of vegetable matter buried in the rock underwent a like change, and now appear largely in the form of graphite.

Original layers of the phyllite.

From these last considerations it is evident that the lamination, so characteristic of the phyllite, has no necessary connection with the original layer structure of the mud or clays. It becomes an interesting problem for us to determine, if possible, something in regard to these original layers, that we may the better understand the changes in position that may have taken place. All that we have been able to find that gives us indications of the original rock layers is the variation in the phyllite noticed in the descriptions of the different phases or bands at the railroad cut near Bloomingdale. The graphite bands and the chiastolite band, alternating with bands of the normal phyllite, indicate layers or strata varying in composition, hence probably indicate the layers or strata in the original sediments. As these bands are now parallel with the lamination of the phyllite, the indications, so far as they go, show that the original strata, at least in this place, have been upturned or folded so as now to stand almost vertically. In no other place do we

Railroad Cut at the Summit on the B. & M. R. R.

find so good opportunity to trace out the original structure of the rock; so, reasoning from this, until there is something found to the contrary, we may conclude, in general, that the lamination is parallel with the original structure of the rock.

Phyllite at the Summit.

Though we have now traced the phyllite back through chemical and dynamic changes to the original sedimentary strata, the study of this rock is not complete. There are still localities of great interest which present facts not yet pointed out, or not so well illustrated elsewhere. Such a locality is the railroad cutting near the Summit station on the Boston and Maine railroad. Let us begin in our study at the end nearer the city. The rock here is the phyllite not to be distinguished from that first described, occurring in Court Hill. We take the dip and strike, and find the laminae pointing nearly north, and dipping thirty degrees to the west. We do not progress far in our observations before we notice that the ledge is cut by many quartz veins. These are made up of milky or glassy quartz, and vary in thickness up to eighteen inches. There is no regularity in the position of these veins. It is impossible, generally, to trace one of these veins more than a few feet, for they do not extend regularly and continuously, as veins usually do; but they have been involved in the folding and crumpling to which the rock has been subjected. As a result of this, in addition to the complex folding which they present, they have been compressed in places so that they consist of bulging masses; at other places they have been squeezed out to mere filaments or streamers. To such an extent have these veins been modified, that rarely can the parts of the same veins be matched. In fact, the folding, and crumpling, and squeezing together, and pinching out and stretching, have gone so far in places as to produce a perfect medley of schist and quartz veins. These facts have their meaning and contribute to the history of the phyllite.

Folding of quartz veins.

The quartz veins tell us of the extensive fracturing of the rock, by which both large and small fissures were formed. Waters then carried in quartz, filling the fissures and mending the fractures. At a later time this rock was subjected to tremendous pressure exerted against the edges of the laminae. So great was this pressure and such the condition of the phyllite and quartz of the veins that they were no more resisting than is clay in the potter's hand, and both were crumpled into innumerable folds and faults.

Double carbonate of iron and calcium.

While studying the quartz veins our attention is attracted by the rusty appearance presented by a part of a vein. On closer observation we see that the rusty part is not glassy quartz, but is soft and easily scratched by the knife blade. The mineral has a cleavage, and tends to break into rhombohedra. A drop of hydrochloric acid tells us, by the effervescing, that the mineral is a carbonate. The iron rust everywhere coating it tells that iron must be in this mineral. It is in reality a double carbonate of iron and calcium. We may think of it as calcite in which a considerable part of the calcium is replaced by iron, and the mineral is called ankerite. This mineral occurs quite generally with the quartz, constituting a part of the vein. It too must have been brought in and deposited by water, either when the quartz was deposited, or later in cavities occupied by some other mineral, which was deposited with the quartz and was subsequently removed. But this calcite is by no means fixed in its position. It is soluble in water containing carbon dioxide or carbonic acid gas. It may be taken up by percolating waters, and carried until, because of the escape of the carbonic acid gas from the water, the mineral is no longer held in solution and so is deposited. Now and then we may find a considerable vein composed entirely of calcite, but not crumpled and deformed as are the quartz veins. These are later vein deposits. This redeposited calcite is also more nearly pure calcite, indicating that the iron, to a considerable extent, rusted out as solution took place. In these veins may be found, now and then, quite perfect calcite crystals.

Micaceous quartzite or quartzose mica schist.

On continuing our observations beyond the bridge we find that the rock is much more quartzose than before—in fact much of it may be called a micaceous quartzite. It is possible that this part of the cutting belongs with the next formation to be described, and that here is where the one begins and the other ends. If so, this is a contact. At any rate the two are so closely connected that we shall make no serious mistake in considering this rock at this time.

Crumpling in micaceous quartzite.

One variety is of a paper thin, fissile structure, of a grey color, a shade or two lighter than the normal schist, and somewhat rusty in spots due to the rusting of crystals or particles of iron pyrites distributed through the rock. Another variety is a grey, apparently massive, hard quartzite, which, on freshly broken surfaces, shows very little trace of lamina-

Folding of Phyllite and Included Quartz Veins at Deep Cut Near Summit Station.

tion. On careful inspection this variety exhibits a crumpling and crinkling which, for fineness and delicateness, are simply marvellous. This is specially distinct on weathered surfaces because the edges of some of the laminae are more rusty and are thus brought out by difference in color. This greater rustiness of some laminae is due to the impure calcite distributed in these, as is shown by the effervescing seen under the magnifying glass when the rock is touched by a drop of hydrochloric acid. The smooth surface of a joint, or of a drill hole, may present a wavy structure so fine and delicate and nicely colored as to rival in beauty the graining of the choicest woods. From these exceedingly fine folds, we observe all grades up to the coarse ones that may be measured by feet.

Difficulty in estimating thickness of this formation.

In this connection we may see how difficult it would be to determine the thickness of this formation. It is quite evident that the result would be far from correct, if measurement were made directly across the edges of the laminae. In the first place the laminae may or may not be parallel to the original stratification; and, in the second place, because of the crumpling and folding, there is no telling how many times the same laminae are repeated within a given area. For this reason, wherever we give the estimation of the thickness of a formation, it will be based on other facts than the mere measurement across the edges of the laminae. At the best, an estimation of the thickness of the phyllite, which will be given in due time, will be but approximate.

Thus far by the study of certain localities we have attempted to gain ideas generally applicable to the phyllite as a whole. There are, however, variations in it which are only local, and these variations are well worth our study, if we wish to gain a complete idea of this interesting rock.

Finely ribbed phyllite.

Following the electric car road from College street along the side-hill on the way to Auburn, we are walking over this same phyllite, as we may easily see from numerous outcrops. After we have gone about a mile and a half, there appears a local phase of this rock that is very noticeable, and at times beautiful. Here the rock has a light grey color, metallic lustre, smooth greasy feel, but does not leave a mark on paper; it breaks into large, flat, thin slabs, the surfaces of which are finely and beautifully ribbed. This delicate ribbing, combined with the metallic lustre, and the light, almost silvery,

color, gives to this variety a special beauty not often seen in this rock. The ribbing is so regular, that, at first, the little ridges and furrows seem continuous, lengthwise, across large specimens. On closer examination, the ridges and furrows are seen to constantly fade out, and others as imperceptibly to appear parallel to the former, thus continuing the ribbing. Nor is this ribbing all of the same degree. There are the coarser ridges, but a small fraction of an inch in height, and removed from the adjacent ridges on either side by but a small part of an inch; on these are imposed still finer undulations, and so on until the folds are too fine to be seen. It is in fact a rock surface wrinkled to the superlative degree. But what does this wrinkling mean? It tells us of a secondary change within this rock. After the ancient sediments had been crystallized, and the laminae formed, as previously explained, this rock was subjected to a pressure applied along the edges of the laminae and in the plane of the laminae, at right angles to the direction of the former one that produced the laminae; and the rock, possessing little strength and allowing of considerable freedom of motion between the laminae, yielded in infinitesimal folds throughout its mass. These fine folds constitute the beautiful ribbing. But these minute folds have a deeper meaning. Look at the edge of a specimen where you see the ends of ridges and furrows. There are lines running across this broken surface where successive laminae, one above the other, have either been pinched out to nothing or broken off. When a specimen is broken across the laminae, the breaking tends to follow these lines. These are lines of an incipient slaty cleavage. These little folds are really the laminae in process of rotation in minute sections into a plane at right angles to the original foliation. This rotation stopped at just the right stage to teach us a most interesting lesson. Something quite similar to this was pointed out near the east end of the railroad cutting at Bloomingdale, but in the case of the latter there is wanting the beauty that accompanies the former. This minute wrinkling of the schist laminae is quite generally characteristic of the rock, but nowhere else is it found in such perfection as on this side-hill in Auburn.

Development of a new structure.

Mica schist phase containing garnets and staurolite.

Continuing on in our journey, following the electric car track to the road leading from the continuation of Southbridge street up on this hill, we walk along this road to the road leading to Auburn, then turn

Crumpled Phyllite from Auburn. Original, 5 Inches by 4.

off on the road leading to John C. MacInnes's place, and find ledges near Mr. Nye's house. The rock is a rusty mica schist more coarsely crystallized than is the normal phyllite, yet a part of the phyllite band. It is characterized by a peculiar odor, when breathed upon, not at all resembling the argillaceous odor common to the schist. In these ledges may be seen many little garnets, one every now and then showing the regular form of a rhombic dodecahedron. This figure may be recognized by a single crystalline face having the shape of a rhombus. With these may also be seen small, dark grey, prismatic crystals, some of which cross each other, or branch one from another. These are crystals of staurolite. They are, now and then, found in this mica schist, though less commonly than the garnets. The latter may also be found in considerable abundance in the outcrops near the centre of Auburn. The development of these minerals within this comparatively small area probably indicates that beneath, at no great depth, is a mass of granite, and the intrusion of this in a molten condition produced a little higher degree of metamorphism or change in the rock, resulting in the formation of these minerals.

The study of these phases of the phyllite will certainly repay us for an afternoon's journey on the electric car over this Auburn hill. Looking to the north from this hill we admire the beautiful view of the hills across the valley, and we take note of a deep notch in the horizon. This marks an ancient river valley, the valley now occupied in part by the Holden reservoir.

Andalusite phyllite.

In walking over the side-hill sloping down from the Boston and Albany railroad to Lake View one may notice, now and then, bowlders which may possibly attract attention. They are fragments from ledges somewhere to the north; but just where the ledges are, is not known, though probably they are not far. The rock of these bowlders is of a dull dark grey, almost black, color. It is, apparently, not crystallized so much as is the normal phyllite, though the many little glistening points show that the crystallization is well advanced. It is thin bedded in structure, the laminae averaging about one eighth of an inch in thickness; and the cleavage between these is less marked and distinct than in the phyllite generally. Through this black, dull, laminated mass are distributed little, white, prismatic crystals, about as large in diameter as a fine pin, and from one eighth to one half inch in length. These crystals

lie in planes parallel to the laminae, and are generally of a dull white color. Possibly this dullness may be due to the weathering which the bowlders have undergone. These little white crystals are the mineral andalusite, and this phase of the phyllite may be called an andalusite phyllite.

Chiastolite schist of George Hill, Lancaster, a part of this same formation.

This phase of the phyllite reminds us of the beautiful chiastolite[1] schist which occurs so abundantly in bowlders on George Hill in Lancaster. The mica schist of this hill is a northern part of this Worcester phyllite area, and contains large, beautiful crystals of chiastolite clearly marked by distinct crosses appearing in the ends of the crystals. These crystals are frequently an inch in diameter, and several inches in length. Moreover, we may notice in some specimens what were evidently crystals of chiastolite, but which are now simply masses of mica preserving the shape of the chiastolite crystals. This illustrates how one mineral may change into another, while imbedded in the rock, assuming the crystalline form of the new mineral as in the mica scales, yet the whole mass of scales preserves the shape of the original crystal.

Anyone at all interested in this subject should not be without a specimen from this George Hill locality, and there is no reason why he should, for nice specimens may be found by the roadside and in the stone walls on almost any part of this hill.

Geological age of the Worcester phyllite.

In this discussion of the Worcester phyllite there is one point which we have thus far entirely neglected. To the geologist the study of any rock, especially if it be a sedimentary rock, or a recrystallized sedimentary rock, is not complete until he knows where to place it in the earth's history. Through many changes has the earth come to its present state. There has been a development, both animate and inanimate, and the record of these is buried in the rocks. From their study must this history be revealed. But this history is long and complex; so, for the sake of simplicity and system, just as the history of man is divided into various ages, the history of the earth is divided into certain periods. The names of these, as adopted by the geologists of the U. S. Geological Survey, are, beginning with the earliest: Archean, Algonkian, Cam-

[1] Chiastolite is a variety of andalusite, which shows a cross when the crystal is broken so as to present a cross-section.

brian, Silurian, Devonian, Carboniferous, Juratrias, Cretaceous, Eocene, Neocene, Pleistocene. These periods are not equal, either in length of time represented or in the amount of the earth's development that took place in them. The older or earlier periods, because their records are more nearly obliterated and less easily deciphered, represent longer durations of time and greater changes; while for the more recent periods greater detail is possible, leading to more frequent and shorter divisions in the geological history.

Therefore, before we leave the study of the Worcester phyllite, let us try to determine where it belongs in this scheme, that we may know what relation it bears to the development of the earth. To determine this in the case of a rock is not always easy, especially in the case of a recrystallized sedimentary rock, for the records have been largely, if not entirely, destroyed, during recrystallization. In spite of the changes through which this phyllite has passed, fortunately a few fossils have survived. These have already been described in our discussion of the rocks found at the coal mine. These fossils fix quite definitely the period in the earth's history to which this rock belongs. They are the geological coins. They indicate that this rock belongs to the Carboniferous, and thus it is brought into its position alongside of, or near to, in geological time, the rocks containing the coal beds of Rhode Island and Pennsylvania. This was suspected by many long before the fossils were found. The graphite and graphitic anthracite layers, met with somewhat frequently in cutting into the phyllite here in Worcester and in other places, tell of a large amount of buried vegetable material, just as the beds of coal tell of an ancient vegetation. Moreover the degree of recrystallization exhibited by the Worcester phyllite is not greater than that exhibited by parts of the Carboniferous of Rhode Island. Considerations like these led Sir Charles Lyell, about 1843, to conclude that the rocks of the Worcester coal mine were of the same age as those of the coal formations of Rhode Island; and, undoubtedly, the same idea was in the mind of Louis Agassiz when, standing at the mouth of the old coal mine, he prophesied that some day fossils would be found there.

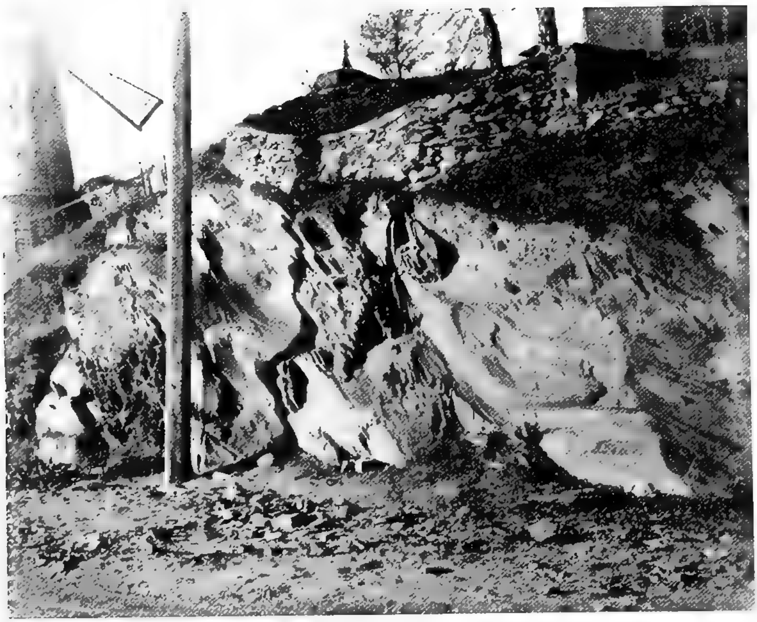
CHAPTER II.

WORCESTER QUARTZITE.

The phyllite, thus far considered, does not make up the whole of the rock-floor beneath Worcester. We become aware of this when we examine the ledges outside of the area already pointed out and indicated by the blue color on the geological map. Let us go out Highland street or Pleasant street to the cemetery just beyond Newton square; there, by the side of the street and in the open space opposite, will be found ledge. A glance at this is sufficient to convince us that it is not the phyllite. We must remember that this ledge is an index of what is beneath and around for some distance, for it is really a part of the rock-floor. Let us examine this rock carefully as we did the phyllite.

Description of micaceous quartzite.

It is of a dirty grey color on weathered surfaces, but within is of a slightly reddish or brownish grey. It breaks with difficulty, but when it does break, the pieces fly, showing both its toughness and elasticity. The surface of the rock, where it is broken, is frequently concave like the inside of a shell, on account of which we say that this rock has a conchoidal fracture. It is hard; and it quickly dulls the edge of the steel drill. It would furnish excellent macadam for our streets. Under the magnifying glass, we see it to be compact, of a finely granular texture, and made up of glassy quartz and, in small part, of very fine scales of brownish mica. This hard rock is, then, practically made up of finely granular quartz, and we may rightly call it a quartzite. We notice also a banded structure, the layers varying from an inch or so to many inches in thickness in the weathered ledge. In cutting into the rock the workmen find it much more massive, and the fissile structure less clearly marked. Frost and other atmospheric agents bring out the fissility by separating the sheets and enlarging the divisions between them. The layers have a uniformity in position, lying parallel to each other, though we may here and there find unimportant curves and bends. In general they point or strike nearly north and south. This



Ledge at Foot of Chadwick Street.

fact will serve as an index, pointing to the direction in which we may look for the greater extension of this rock. Moreover the beds are almost vertical in position, having a dip of about 75 degrees to the west. Hold a closed book before you, resting the back on a horizontal surface, and in such a position that it points 5 degrees east of north, and the leaves slope down to the west, making an angle of 75 degrees with the horizontal plane; the leaves then represent quite accurately the position of the beds of this quartzite.

Micaceous quartzite beneath Newton Hill.

But we know somewhat in regard to the extent of this quartzite in this vicinity. In digging the trench for the sewer through Pleasant street, west of Newton Hill, and also in the western part of Highland street as far east as Park avenue, the workmen dug down to the rock-floor beneath, and found this floor to consist there of the same hard, tough quartzite. As the beds beneath one street are parallel with those under the other, and point towards them, we may safely conclude that they are continuous and extend under Newton Hill. Having found that this rock makes up somewhat of the rock-floor beneath Worcester, let us determine accurately its extent. It has been pointed out that the beds point in a northerly direction. Let us go to the north in search of outcrops that we may know what kind of rock is there in the rock-floor.

Micaceous quartzite in Grove street at corner of Chadwick.

Passing out Grove street to the corner of Chadwick, we come to an excellent outcrop. The rock immediately attracts our attention, rising, as it does, in a vertical wall 12 feet or more in height by the side of the street. The rock is made up of clearly marked laminae. These vary in thickness, but are generally not more than an inch thick. In some cases, where the rock material was favorable for such development, they are almost paper thin. Breaking into the rock, we find that the description of that near the old cemetery in Pleasant street (see page 30), exactly applies. It has the same color, hardness, toughness, conchoidal fracture, and is made up of the same materials,—is, in fact, the same rock. The two are as much alike as they might be if they were not more than 100 feet from each other. By means of the compass we take the direction of the strata, and find that they point 25 to 30 degrees east of north. They dip 43 degrees to the west. We

notice a decided variation in the position of the beds here from that of the like beds in Pleasant street. There can be no reasonable doubt, from the identity of the two rocks, that, if the loose covering were removed, we should find rock like these two outcrops making up the rock-floor between. As there is a decided variation in the strike and dip at the two places, it is evident that these beds do not always follow straight lines, with uniform slant, in this rock-floor, but curve and bend in wavy bands.

Origin of the micaceous quartzite.

As we look at the ledge here at Chadwick street, we are impressed with the nicety or perfection of the lamination. On breaking into it, we find that there are two other facts revealed. There are cross-joints running in almost every direction on account of which these beds break into irregular, sharply angular blocks varying greatly in size. The other fact brought to light is that the material in some beds has a regular arrangement in bands indicating that these beds are made up of layers. There is also an indication of a layer structure on a larger scale in the ledge as a whole. In examining the rock we find these variations evidently due to a variation in the relative abundance of quartz and mica. One stratum, a foot or more in thickness, is thinly fissile and very micaceous; the adjacent one is thick and massive and lacking in mica. In this way the ledge, as a whole, may be divided into strata which may be traced far into the ledge. This layer structure, indicated by the banding, gives us the first chapter in the history of this rock. This structure clearly points back to a time when this rock was made up of strata differing slightly in composition. They must have been formed by currents of water just as rock strata are being formed at the present time. When the current can no longer carry or push along the particles of broken rock, it there deposits them. Every little brook shows us, on a small scale, how the larger currents do this work. But the material contained in, or constituting, this rock tells us also just what those particles must have been. The great mass of this rock is glassy quartz with a little very fine mica. The quartz tells us that most of the particles deposited by those currents must have been particles of quartz in the form of sand—grains of sand rolled and washed, just as grains of sand are now rolled and washed along the shore. The fine mica tells of a small amount of clayey impurity mixed with the sand. But the rock at present shows us nothing appearing

Part of Ledge at Foot of Chadwick Street, Showing a Fault.

like grains of sand; and the mica is in no respect like particles of clay. Though the quartz is granular, it does not present the granular appearance of grains of sand. It is too compact and fine; it has rather the granular texture produced by crystallization, and the mica scales are certainly minute crystals. This rock, which is clearly crystalline in texture, bears or preserves the indubitable marks of a sedimentary, fragmental rock. It, then, like the phyllite, must have been partly recrystallized; but instead of beds of clay or mud at the beginning, it consisted of beds of sand. These passed through a crystallization, like that of the schist, under the influence of heat, moisture and pressure. The grains of sand were, in part, dissolved in the hot moisture under pressure, yet not sufficiently dissolved to obliterate the original layer structure of the sand. In due time the dissolved quartz, being no longer kept in solution through the cooling of the rock and the relief from pressure, recrystallized, filling the interstices between the undissolved grains, and the clayey impurities crystallized into mica. When a very thin and transparent section of the rock is examined under the microscope the original, angular grains may still be seen in part.

Fault. Another fact may be noticed, in looking at this ledge, which shows clearly that there has been differential motion here.[1] The edges of the beds on the right slope up diagonally across the face of the ledge in somewhat wavy lines; while on the left the beds form a flattened arch with the edges almost horizontal, and the arch pitches down to the south at an angle of about 20 degrees. The beds of this arch are not parallel with those of the ledge generally, and the region where the two meet near the middle of the figure gives evidence of a breaking and crushing of the rock. It is evident that one part of this ledge has been moved against the other part. When there is a break in a rock in this way, and the beds on one side do not agree with, or match, those on the other, there is said to be a fault. In the midst of the rock on the Chadwick street side of this ledge may be seen something similar, where a part of the beds, possibly less resisting or weaker, were folded, while the stronger beds on either side were not folded. In other words we find in this small outcrop abundant evidence that this rock mass has not moved as a unit, but one part has had one motion, and another part another motion, producing breaks and want of uniformity in position of adjacent strata.

[1] See plate opposite.

Quartzite in Dodge Park.

Leaving this outcrop at Chadwick street, we pass still farther north to the ledges appearing in Dodge Park. This rock at first appears quite different from that last examined. It shows none of the bedding so noticeable in that, but breaks into exceedingly irregular, angular, generally small, pieces. On this account it is difficult to obtain specimens of good shape. On breaking into this rock, we find it of a grey color, hard, compact, destitute of lamination, but cut by fissures in every direction with no regularity. There may be seen also innumerable, fine, at times capillary, veins of quartz running through this rock. So abundant are these as to put one in doubt as to which constitutes the larger part of the ledge, the veins or the original rock substance. Surfaces of the ledge frequently present a perfect network of these veins where the weathering has removed the softer rock material. As we are studying these under the magnifying glass, our attention is attracted by little shining particles of iron pyrites. To these is due the iron rust so abundant in the fissures and noticed when the rock is broken. Taken as a whole this rock is a grey quartzite, in composition resembling that in the ledges by the side of Chadwick and Pleasant streets. It differs from those most markedly in lacking the laminated structure. Possibly it had that structure at a former time; but if so, since then, it has undergone a violent disturbance by which it was completely shattered into fine fragments, and afterwards solidified by the deposition of quartz in the fissures. It may be that we are in error in considering this ledge as belonging with those observed in Pleasant and Chadwick streets, but if so, the error is not serious, and will not generally affect our conclusions.

Extension of the quartzite.

In this way, by examining the ledges one after another to the north, we may find what part of the rock-floor is composed of quartzite, and we may also draw quite accurately by means of the outcropping ledges and the direction of the beds or laminae, a line separating the area of phyllite from that of quartzite. In like manner we may work to the south. Putting these results together we may clearly see that this quartzite forms a band in the rock-floor extending parallel with that of the phyllite and lying to the west of it. So intimately associated are these two that whenever one is found the other is found east or west of it. That part of Worcester under which the band of quartzite extends is represented on

the geological map as accurately as we have been able to determine it.

Phyllite between Dodge and North Parks.

From this digression, to point out the extent of this quartzite band, we resume our study of the ledges, passing from Dodge Park to North Park. On the way we note the ledges appearing by the side of the street leading to Burncoat street. In these ledges we at first notice considerable reddish grey quartzite, practically the same as that we have been studying; but this grows less abundant as we proceed until the rock is all phyllite. We have crossed the line between the two. But here the line is not clear and distinct, the reason for which will appear when we consider the relation of these two rocks to each other. We take the dip and strike of the laminae, and find them pointing about north and south and having but a slight slant or dip of 20 degrees to the west. We contrast this flatness with the almost vertical position of the phyllite laminae in other places where we have studied. All these facts must be taken into consideration as we attempt to interpret the geology of this region; and our work is not complete until we have fitted all together as the parts of a puzzle.

Crushed granite in North Park.

Passing into Burncoat street and turning to the south, we notice a rock in the gutter of the street. It is neither of the rocks thus far studied. Continuing, and turning into North Park, in the vicinity of the boathouse, we find more of this peculiar rock. We are able to go around the area in which this rock is found, as it extends but a little outside of the park. This area is indicated on the geological map. This rock is of a slightly brownish grey color; has a marked foliated structure, tends to break in thin sheets with somewhat irregular surfaces. These surfaces are of a brownish color, and present an abundance of thin brownish mica as a veneering. This is about all the mica there is in the rock. It is this arrangement of the mica that gives the foliation to the rock. These surfaces of the folia also present, under the glass, the appearance known as slickensides. The surfaces are polished and marked by fine striations parallel to each other, as if there had been a sliding of one surface on the other. Looking at the cross-section, we see that the rock is of medium fine, granular texture and contains an abundance of quartz, white and glassy. There is also much feldspar, as is indicated by the shining cleavage surfaces which flash in the

sunlight. Most of the feldspar is so fine as not to be easily distinguished from the quartz, but, here and there, is a well defined particle, the largest being an eighth or a sixteenth of an inch through. Some of the feldspars are lens-shaped. Under the glass may be seen little, dark grey particles, probably magnetite, as there is a considerable quantity of magnetic material in the powdered rock. In the rock, but not of it, are also many coarse veins of glassy quartz. This rock is at first very perplexing, as it resembles the neighboring rocks only in its foliated structure. Considering the composition of this rock it is essentially a mixture of feldspar and quartz, if we leave out of consideration the veneering of mica on the folia. Occurring as it does in this small area, without any connection with the neighboring rocks, its composition and occurrence indicate that it is a granite. But a granite of itself would not have this foliated structure, nor would the mica be arranged in this way. It is more than a simple granite. The foliation and fragmental granular texture, rather than crystalline granular texture, and the veneering of mica, all point to a dynamic change or rearrangement within this rock. It has been crushed, and so thoroughly that only now and then did a feldspar escape. The pressure producing this crushing was not parallel to the folia, but across them at a larger or smaller angle, thus producing a shearing motion within the rock-mass by which the substance was arranged in folia. At the same time these folia rubbed, one against another, producing the slickensides, and transforming the feldspar on the surface into a veneering of mica. This strange rock is, then, a crushed and sheared granite.

Micaceous quartzite in North Park.

Having digressed from our study of the quartzite to study this small area in the park, we continue our observations, and, near the southeast corner of the park, come to a rock that looks familiar. It is grey in color, and laminated; the edges of the laminae point thirty-five degrees east of north and dip fifty-two degrees to the west. Breaking off a piece from the ledge, the rock proves to be the slightly brownish grey micaceous quartzite. But we carefully note that between this and the band of quartzite already traced to the west is a band of phyllite appearing in the outcrops noticed as we approached Burncoat street. This is also indicated on the geological map. Before trying to solve this problem and interpret the meaning, let us continue our observations, because we remember that along

Quartzite in Lincoln street.

Lincoln street, as we go down the hill towards the Poor Farm, we have seen many ledges. Going to these, we find them to be the same brownish grey micaceous quartzite, but a little less hard and firm, especially near the weathered surfaces. Another fact noticed is that some of these surfaces are irregularly pitted. These cavities sometimes reach an inch into the rock, and may be an inch and a half long by a half inch wide. These are seen only on weathered surfaces, and we immediately attribute them to weathering. But why should one part of this rock be affected so much more than another? We break into the rock to reach that which the agents of the air have not yet acted on. The rock within is not uniform. There are small masses of a soft, white mineral corresponding in size and shape to the cavities on the weathered surfaces. A drop of hydrochloric acid on this white mineral tells us, by the effervescing, that the mineral is calcite. The explanation of the cavities is now clear. Calcite is quite readily soluble in water containing carbonic acid, and hence is dissolved by the rain water falling on these rock surfaces, leaving the cavities which the calcite filled.

Calcite in the quartzite.

Fine quartz veins in the quartzite.

There are here also many veins of white glassy quartz, and these are frequently so abundant and fine as to make a perfect network or lacework through the rock. These veins, as has been pointed out before, are simply filled cracks or fissures. These show clearly that, at some stage in the history of this rock, it was subjected to some disturbance which completely shattered it.

Variation in strike of the quartzite in Lincoln street.

Here also we note the direction of the laminae, for this may help us in solving problems, before we are through with the subject. Near the top of this hill the direction is thirty-five degrees east of north, and the dip is fifty-four degrees to the northwest; part way down the hill the strike is forty-three to forty-five degrees east of north, and the dip forty-eight degrees to the northwest; still farther down the hill the strike is fifty degrees east of north, and the dip forty-seven degrees to the northwest. As we go down this hill in Lincoln street, approaching the Poor Farm, the rock laminae point more and more to the east. We are evidently, then, following a curve in the rock laminae, which we should find continuous were the loose material removed so that we could see the rock-floor.

This has its meaning which will appear in due time as we proceed in the study.

Moreover, as we examine carefully and study the rocks in this area, in one part of the ledge, where the laminae point fifty degrees to the east of north, we observe, in some of the freshly broken rock, a distinct banding. This is due to a slight variation in the relative quantities of quartz and mica constituting the rock. This variation and banding probably point back to the layers in the sand out of which this rock was formed. These bands are not here parallel with the sheets into which the rock splits, but cut across them, having a direction more nearly north. Hitherto, where banding has been observed, the banding and splitting have been parallel (the layers so formed are called laminae), having a common direction of about thirty degrees east of north. This exception brings out clearly a secondary splitting caused by pressure, that may cut across the bedding, and the sheets so formed, which are called folia, may be just as firm and strong as when they are parallel with the bedding. The foliation is later and independent of the bedding, and is due to pressure and a rearrangement of rock particles as the rock underwent changes in position.

Quartzite on Green Farm.

Without attempting, at this time, to explain and interpret all of the facts which may shed light on this area, we turn into the fields, and go up on Millstone Hill, passing to the west of the summit, near the shore of the pond on Green Farm. Here we find numerous outcrops in the form of a light grey, thinly foliated quartzite, which is, at times, quite micaceous. It is not unlike the quartzite found along Lincoln street. We also take the direction of the laminae, and find they strike sixty degrees east of north, and dip thirty-nine degrees to the northwest. If we compare this direction with that in a like quartzite found just northwest of the coal mine, on the other side of the hill, where the laminae point fifty-five degrees west of north and slant forty-four degrees northeast, and then think of what would be observed, if we could study the intervening rock-floor by ledges as we did the rock-floor down Lincoln street, we can see that we should find the laminae gradually changing in strike from sixty degrees east of north to fifty-five degrees west of north, and the direction of the dip or slant from northwest through north to northeast. In other words the laminae curve or wrap around the northern side of this hill. The curve in the laminae in the

Lincoln street area was parallel with this, only a little more removed from the hill.

Quartzite in East Kendall street.

We now continue our observations, going towards Belmont street, and keeping to the level of the previous observations on the side of the hill. We frequently find the same quartzite at the surface, and a good place for us to stop for observations again is at the foot of East Kendall street. Here is the quartzite, again of a slightly reddish or brownish grey color, and thinly laminated. Again we take the strike of the laminae, and find them pointing seventy degrees east of north, and dipping eighty degrees to the south. Here is a decided change in the dip. At the foot of the last or most southerly pond on Green Farm the laminae were dipping to the northwest, while here they dip to the south. If now we place one hand with its back sloping off to the northwest and pointing about sixty degrees east of north, and the other hand near the first and pointing seventy degrees east of north with its back slanting down eighty degrees from the horizontal, it will be seen that the two hands are parts of a fold which has a gentle slope to the northwest and a steep slope to the south. In other words, in this short space, we have crossed a fold in the beds of the quartzite. Doubtless there are numerous other folds like this which we are not able to trace out so clearly, for this quartzite has been marvellously folded, as we shall see before we are through with its study. But there is another important fact for us to notice here at the foot of East Kendall street. Following the direction of the laminae easterly, and only a few feet, we suddenly come to an entirely different rock. This we recognize as a part of the granite of Millstone Hill, of which we shall speak in due time. In our minds, then, we can see what would be exposed, if the loose earth of the street were removed—the laminae of the quartzite striking directly against the granite of Millstone Hill, and the granite attached to the quartzite securely, yet the line between the two clear and distinct. Doubtless we should be able to trace this quartzite, bearing the same relation to the neighboring granite, south across Belmont street, thence around the foot of Normal School Hill, if it were not for the covering of loose earth spread over it. This quartzite probably underlies East Worcester; and how far up towards the centre of the city it extends cannot be positively stated, but at the time of the excavation of the cellar of the new city

Relation of the quartzite to the granite of Millstone Hill.

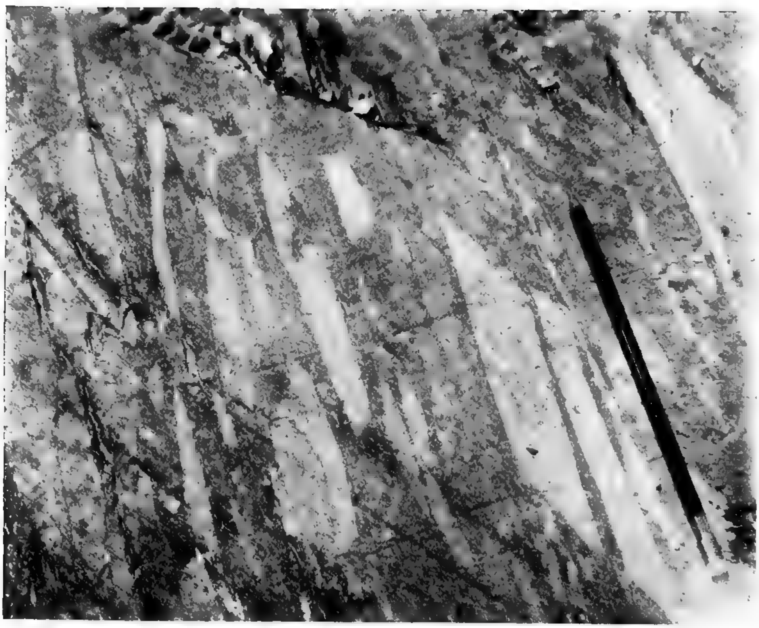
hall, the rock-floor there exposed was this same quartzite. Relying on this we represent the quartzite on the map as extending under the city as far as that point. But returning to East Worcester and following around Normal School Hill, only a spur of Millstone Hill, at the corner of Hunt and Shrewsbury streets, and also on the opposite side of Shrewsbury street, we find ledges having a familiar appearance. The rock is massive, without lamination, but cut by joints crossing each other in various directions. Along these joints the rock has weathered away leaving creases in its surface. On the outside this rock is of a dark, dirty grey color; but within is of a light greenish grey, sparkling with little black crystals of ottrelite. Under the magnifying glass, the rock is a mass of fine, glassy particles of quartz.

Quartzite at the corner of Hunt and Shrewsbury streets.

Breccia near Shrewsbury street.

A few hundred yards east and southeast, on the border of this quartzite area, and evidently closely connected with the quartzite, is another rock worthy of considerable study. It may be found by the side of the dummy railroad track, and also between this track and the tracks of the Boston and Albany railroad. These ledges are not a part of the railroad cutting already studied under the Carboniferous phyllite, but are nearer the city. The rock is of a dirty, dark grey color, has a noticeable lamination, so that we may take the dip and strike. We find this rock pointing thirty-five degrees east of north, and the laminae standing almost vertically, but dipping seventy-eight degrees to the southeast. If we compare the position of these laminae with that of the phyllite laminae just east in the railroad cutting, we find that while the two agree in direction, those of the former dip to the southeast and those of the latter to the northwest. If you will place your hands so that they point thirty-five degrees east of north, and the right hand slopes down or dips seventy degrees to the northwest, while the left dips seventy-eight degrees to the southeast, the relation of the laminae in these adjacent rocks will clearly appear. The hands slope towards each other, and indicate the trough of a fold. There is then in the rock-floor here a fold with the concave side of the fold up; this is a synclinal fold. It is another evidence of the folding that these rocks have undergone.

But to return, in thought, to the rock itself, let us carefully examine it. It has a blotched appearance, the blotches being



Part of Surface of Ledge of Breccia, with Glacial Marks Extending Diagonally Across.

several shades lighter than the general surface of the rock. There is no regularity in the shape of these. Some are long and narrow with rounded ends; some are irregularly diamond shaped with sharp angles; some are as wide as long, and partly angular and partly rounded. On the surface of this rock may be seen in places the glacial scratches pointing seven degrees east of south. On breaking into this rock so as to examine a fresh surface, we find the rock within much like that outside, only a little darker. The blotches consist of fine, granular quartzite, of a grey color, closely resembling the quartzite already described. In fact the quartzite of these blotches and that of the ledges a few hundred feet away are near enough alike to have been side by side in the same ledge. These angular fragments of quartzite are imbedded in a darker, finely grained crystalline matrix consisting, as far as can be seen, of little, black, lengthened crystals of biotite or ottrelite. Such a rock, made up of angular fragments cemented by other material, is called a breccia; but as the cementing material has been crystallized, it may not be improperly called a metamorphic breccia.

Relation of breccia to the quartzite.

But it is more than this because of what it tells us of the relation of the rocks we are considering. It tells of the breaking into pieces of the neighboring quartzite, along the border, after the layers of sand from which it was formed had been changed into sandstone or quartzite; then of the forcing of these fragments into the adjacent beds of clay, probably already hardened into shale; and, finally, of the recrystallization of the fragments into quartzite if they were not already quartzite, and of the clay or shale about the fragments into a crystalline matrix.

Quartzite in the "Coal Mine" area.

Continuing our study around the border of Millstone Hill, we go near the State Lunatic Hospital. The only ledges appearing are the granite of Millstone Hill, which we do not care to study at the present time. The ledges lower down on the hill are covered until we come to Plantation street. Here for a short distance phyllite, like that seen in the railroad cutting near by, appears. North of the asylum, though the rock bordering the granite is not seen in outcropping ledges, the numerous fragments of quartzite in the loose material leave little doubt but that this is the rock beneath in the rock-floor. Thus we trace the quartzite along the eastern foot of Millstone Hill to the area northwest of the coal mine, where we find ledges, the

rock of which is identical with that at the corner of Hunt and Shrewsbury streets. It is of a light greenish grey color, composed almost entirely of finely granular, glassy quartz, but cut in every direction by almost innumerable veins of white, glassy quartz. These veins vary in thickness from an inch, or a little more, down to those of capillary fineness. As we have pointed out in other cases, these veins tell us of a tremendous breaking, even shattering, of this rock, and then of the deposition of quartz within the fissures cementing the fragments together into firm and massive rock. The quartzite here also has a distinct lamination. The strike is fifty-five degrees west of north, and the dip forty-four degrees to the northeast. In some of this rock there is a clearly marked layer structure consisting of alternating light and dark green bands, some not more than one eighth of an inch in thickness. These bands point back to the original layers in the sand out of which the quartzite was formed, and indicate the original structure of the rock. Here the original structure and the secondary structure, represented by the lamination, are parallel. Here, in spite of the great changes the rock has been through, the two agree in direction, while in Lincoln street we found the one cutting across the other. It all depends on the direction of the applied pressure. When, as is generally the case, the original sedimentary lamination and the secondary foliation (dependent on the position of the mica scales), coincide we may assume that the mica crystallized between the original laminae under the pressure of the superincumbent beds before the folding, while the folding caused the crushing and quartz veining.

Thence, passing across the fields, we come to Lincoln street, and have encompassed Millstone Hill. We have found its base surrounded by quartzite reaching somewhat up on its sides; moreover we have found the quartzite laminae leaning towards the hill on all sides except the west and southwest, where they strike directly against the granite.

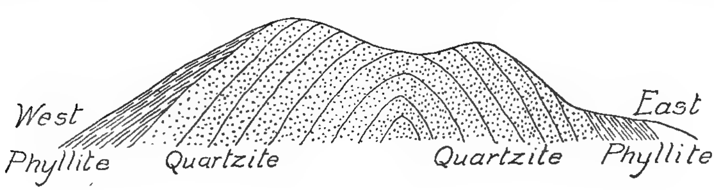
Extension of this Millstone Hill area to Oakdale.

But this band of quartzite surrounding Millstone Hill is not an isolated area; it is the southern extremity of a large area extending several miles to the north. We may trace this area by going into the fields north of Lincoln street, and observing the ledges, as we go along to the north, reaching the Boston and Maine railroad at the large curve northeast of the Summit; thence following the

railroad, and examining the ledges in the hills on either side, we shall find the rock a quartzite, closely resembling that which we have been studying, but frequently pure white in color. It is made up of glassy, granular quartz. This quartzite we may follow until it disappears beneath the sands and gravels of the Nashua River Beyond these it again appears; and is found in the upper part of the high hill just east of Oakdale. It will be well for us to make a careful study of the rocks of this hill, for here are facts of exceeding interest revealing the relation of the quartzite to the Carboniferous phyllite, which we have already studied. Starting from the Oakdale station we go east, and ascend this hill. Immediately we find outcropping ledges of phyllite identical with that which we have studied farther to the south in Worcester. In fact by ledges appearing here and there we may trace the connection of this phyllite east of Oakdale with that in Worcester, and thus show a continuous band. This band of phyllite is parallel to, and west of, the quartzite band already traced from Worcester to Oakdale. These are shown on the geological map.

Oakdale anticline.

To continue our observations on this side hill, we take the strike and dip of the laminae, and find them pointing fifteen to twenty degrees east of north, and dipping thirty-five degrees or more to the west. We then ascend the hill still farther, and, near the top, find more outcrops. The rock in these is quartzite, not phyllite. We also take the strike and dip of the laminae in these ledges. They point twenty-five degrees east of north, and dip about fifteen degrees to the west. In other words the quartzite is sloping down under the phyllite found in the lower part of the hill. Continuing still farther to the east over this hill, we find the quartzite in the ledges, but, after passing the first road extending north and south, we notice a change in the position of the laminae. While they still point in about the same direction, they slant or dip to the east, or in the opposite direction from what they did in the western part of the hill. On going still farther to the east, we find the phyllite also



dipping to the east at an angle of about forty-five degrees. We may represent in the accompanying sketch what we have found in going over the hill.

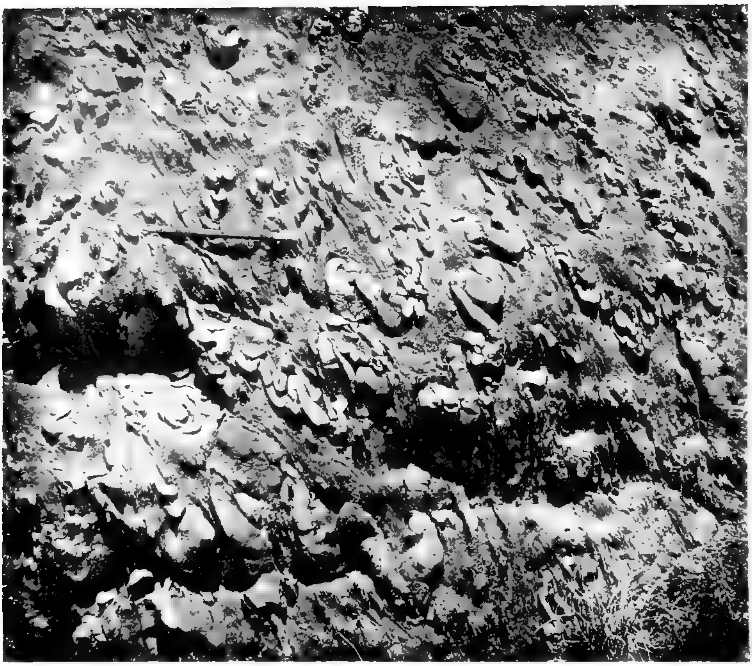
The phyllite leans against the quartzite on the west and on the east; and the quartzite in the western part of the hill leans towards the east, and in the eastern part of the hill towards the west. Putting together these facts, it is evident that we may represent the laminae as constituting an arch or fold. But as this rock-floor has been cut into and worn away by the rivers of past ages, this fold is not now perfect; the phyllite, that once extended over from the eastern side to the western above the quartzite, has been worn away leaving only these remnants on the eastern and western slopes. These are quite sufficient, however, to plainly show us the structure. When rocks are bent into a fold or arch like this, they constitute an anticline or anticlinal fold.

Millstone Hill — Oakdale anticline.

With this key to the problem, we now retrace our steps from this hill across the Nashua river, and examine the quartzite ledges observed in our former study, as we went to the north. We now find the anticlinal fold traceable through the whole area; and, here and there, at the very crest of the fold, we also find small patches of phyllite which have fortunately escaped the erosion, and which tell us plainly that the phyllite once covered the whole of the quartzite, thus completing the fold. The structure of this band of quartzite thus becomes clear until we reach that part encircling Millstone Hill. But what we have seen to the north helps us to understand also this. When this fold was formed, so great was the strain upon the quartzite and phyllite in the Millstone Hill area, that they were broken in the bending, and on the east of this break were uplifted in a fold so as to rest on the granite; while west of the break these rocks were not uplifted, or only slightly so, and the ends of their laminae, left by the break, directly adjoined the granite. At the same time, in the eastern and northeastern parts of this hill, the laminae were shattered, producing the broken structure already pointed out. What connection the granite may have had with all this, we shall attempt to point out in another chapter.

Wigwam Hill.

In encompassing Millstone Hill, we did not stop at Wigwam Hill. The rock in this hill is worthy of more than passing mention. As we go to the southern crest of the hill, we note the position of the laminae or folia which



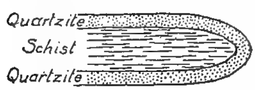
PART OF THE SURFACE OF THE LEDGE AT WIGWAM HILL. THE FOLDED BANDS OF QUARTZ SHOW THE ORIGINAL STRUCTURE; THE STRUCTURE EXTENDING OBLIQUELY FROM TOP TO BOTTOM OF THE PLATE IS THE SECONDARY STRUCTURE.

point or strike about twenty-eight degrees east of north, and are practically vertical. The rock is of a dirty, more or less rusty, grey color with an exceedingly ragged, uneven surface. On examination we find this raggedness due to the fact that there are two kinds of rock substance here,—one of quartz in irregular, wavelike bands, which project beyond the general surface; and the other, that in which these bands are imbedded. The latter is a mica schist. It is softer and is more easily removed by the atmospheric agents, leaving the edges of the irregularly wavy bands projecting and forming the uneven surface. These quartz bands are generally of a faint reddish tint on the weathered surface, and this coloring makes them more noticeable. The most noticeable fact here is the complexity of the folding seen in the quartz bands. If you will think of wet paper, pliable and yielding, spread in a large sheet on the top of a table, and then of two of its opposite edges pushed towards each other, the many folds, which this wet paper will then assume, will hardly outnumber those that may be counted in these bands of quartz distributed through this schist. Fourteen folds were counted in a distance of sixteen inches in one band. We may trace large folds whose sides may measure a foot from crest to hollow; then we may see that these sides are folded into smaller folds measuring but an inch or so; and in some cases we may distinguish folds in the sides of these smaller ones down to the almost infinitesimal folds.

Moreover the folding is not all that may be here observed. In tracing these quartz bands we observe that they are frequently pinched out until they end in knife edges; and then, with a few inches of schist intervening, again appear and continue in a like crinkled condition until again pinched out or cut off. There are thus produced faults almost without number. In places also may be observed the opposite of pinching out—a longitudinal compression by which the band has been thickened, especially at the crest of folds. In fact so complex has been the folding, crumpling, crinkling, faulting and cutting of these quartz bands that it is with difficulty that the observer can trace with certainty the same band many feet.

These quartz bands are composed of finely granular quartz, and are easily distinguished from glassy quartz veins of which there are some distributed through this schist. The rock in which the quartz bands are is a sandy mica schist, thinly laminated, and

shows, at first sight, very little of this folding. This, however, is not as great a contradiction as it at first appears. On the weathered surfaces, we find that the weathering serves to bring out the structure in places, and reveals a folding within the schist quite as wonderful as that within the quartz bands. At times the laminae of the schist fold in and out, thus conforming with the quartz bands; again by pressure a new structure—a slaty cleavage—is produced at an angle with the lamination and the folia project directly in between the arms of a fold of a quartzite band, the ends of the laminae striking plumb against the concave surface of the fold; again the laminae of this schist cut through the quartz band by faulting so that there may be several inches of schist between the ends of the quartz band.



We have thus in detail described the facts observable at Wigwam Hill, that we may the better picture in our minds the conditions that must have prevailed when this folding took place. We find here no evidence of breaking, not even in the brittle quartz. There are neither cracks nor fissures indicating the relieving of tension on the outside of these folds; there is no puckering on the inside; neither does the soft schist seem to have had any difficulty in cutting through the harder quartz. Everything points to a soft mass made yielding and plastic by enormous pressure under which the strength and hardness and brittleness of the quartz bands counted for naught, and the whole was as pliable as so much dough or putty. Nevertheless so gentle were all of the movements that the bands of quartzite and schist did not mingle. While in this condition, by chemical action between the particles, the mica scales of the mica schist were formed, and, as they were formed, grew in the direction of least pressure, as has been before explained, thus producing the schistose structure. After the mica scales had been formed, the folia of the schist were in part folded very complexly as may be observed on weathered surfaces.

We may go back in the history of this rock and think of it as made up of layers of sand—now and then a layer of pure sand, the other layers of sand mixed with much mud or clay. When this material was recrystallized, the pure quartz layers underwent the least change, and are hence most easily traced at the present

time. These quartzite bands, then, preserve for us the original bedding of this rock which would otherwise have been entirely obliterated during the crystallization and folding. In taking the direction and slant of the folia at this ledge, we must of necessity look at this secondary structure because the original structure is so confused as to make the taking of the dip and strike of the original structure impossible. We could not have a better illustration of the way in which secondary structure may supersede original structure in a metamorphosed sedimentary rock.

Fault or warping in structure of quartzite in "Coal Mine" area.

While we are studying the rocks at Wigwam Hill there is another fact worthy of careful thought. Let us compare the position of the folia in this hill with that of the laminae in the coal mine area. Here at Wigwam Hill the rock folia are pointing twenty-eight degrees east of north and are practically vertical, while in the quartzite a few hundred feet northwest of the coal mine the strike of the beds is fifty-five degrees west of north and the dip forty-four degrees northeast. It is evident that the rock folia of one do not agree in position with the laminae of the other in these neighboring localities; but the lamination of the one, parallel to the original bedding, and the foliation of the other, cutting across the original bedding, are, in these recrystallized metamorphic rocks, due, in large part, to one and the same cause, pressure with or without shearing. When the pressure was at right angles to the bedding, the lamination is parallel to the bedding; when the pressure was not at right angles to the bedding, the foliation is not parallel to the bedding, but cuts across the bedding at some angle. It follows from this that if the rock surface between these two neighboring localities were exposed to view, we should find either the foliation that appears in Wigwam Hill diverging less and less from parallelism with the original structure as we go from Wigwam Hill to the quartzite northwest of the coal mine; or else we should find, in the uncovered rock surface, a line of separation between the two structures—on the west of this line the lamination parallel with the original bedding, and on the east the foliation cutting across the bedding. Which of these really occurs is not possible to determine, because the rock surface is so well covered. If it is the latter, that is, a sharp line or narrow zone between the two structures, then there is undoubtedly a fault there; the change from one to the other is marked by a breaking of the rock. But

as the rock was in an exceedingly yielding or plastic condition, as is evidenced by the quartz bands in Wigwam Hill, it is more likely that the former, that is, the gradual transition from one structure to the other, would be found in the uncovered rock surface; and we may call this a warping of lamination into foliation.

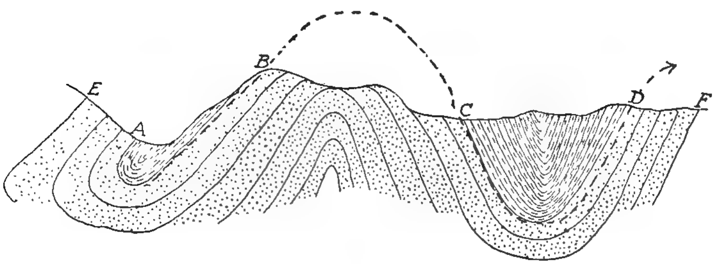
We have already pointed out a sharp synclinal fold between the rocks just west of the railroad cutting near Bloomingdale and the rocks of the cutting itself; this syncline continued to the north extends into this region between Wigwam Hill and the coal mine area, and is the southward extension of the disagreement that there is between the structure of the rock northwest of the coal mine and the structure of the rock in Wigwam Hill.

As we study this rock at Wigwam Hill, the question may arise whether we shall classify this rock with the quartzite or with the phyllite. Tracing the ledges to the north and to the south from this hill, we notice that in some respects the rock comes to resemble the latter; but, taken as a whole, considering its quartzitic composition, it seems best to classify it with the quartzite. Moreover followed to the south, it joins, as we have pointed out, the quartzose band just west of the bridge at Bloomingdale; and in the fields east of Plantation street occurs more of this same micaceous, sandy quartzite, highly crumpled, lying east of the well defined phyllite; and again, farther to the south, a like micaceous, highly folded quartzite is found, even to the Quinsigamond area. On going from Wigwam Hill to the north, we may, in like manner, trace this band of quartzite, always lying east of the Carboniferous phyllite, as far as we have traced the latter even to the northern boundary of the state; but we find, as we go to the north, that the micaceous quartzite becomes a more nearly pure quartzite indistinguishable from the quartzite of the other bands already described. This is also represented on the geological map.

Relation of the quartzite and phyllite bands.

Let us, then, accurately arrange in our minds the salient facts that have been brought out in regard to the areas of quartzite in the Worcester region, especially in the northern part of Worcester. Commencing in the western part of Worcester, as far as we have now studied, and going east, there is a band of quartzite, then a band of phyllite, then a second band of quartzite, then a second band of phyllite, then a third band of quartzite. These bands are ap-

proximately parallel, and the phyllite in the two bands is identical, and the quartzite in the three bands of quartzite is practically identical. It is reasonable, then, to suspect some relation between the two phyllite bands and among the three quartzite bands. In the high hill east of Oakdale we have seen the quartzite dipping under the phyllite on the west, and also on the east; it must be then that the quartzite which dips down under the phyllite comes up to the surface again east and west of the phyllite, under which it goes, thus becoming the eastern and western bands of the quartzite. Adding then to our illustration on page 43 and extending it to



A—B+C—D=phyllite. E—A, B—C, D—F=quartzite.

the east and the west, we may represent the quartzite extending beneath the phyllite, and thus the bands of quartzite are simply parts of one underlying mass of quartzite. South of Worcester, and north from this Oakdale region, the central band does not appear, because the phyllite is continuous from the western quartzite band to the eastern. The phyllite has not been removed by erosion down to the quartzite. At any point, then, where the phyllite appears, if a boring were made through it, the drill would strike the quartzite. This is the relation in position that these two rocks bear to each other.

Thickness of the phyllite. Seeing, as we have, that the quartzite everywhere extends beneath the Carboniferous phyllite, it is quite natural for us to desire to know how thick this phyllite is. It is certain that this covering of phyllite is not of uniform thickness any more than are the glacial deposits above the ledges. There are small areas of this phyllite on the crest of the anticlinal fold, which have been pointed out, and the extent of these areas may be easily expressed in square feet. The thick-

ness of the phyllite in such areas must be expressed by a few inches or, at the most, by a few feet. The surface of the quartzite beneath the whole of the phyllite is far from a uniformly level surface from the very nature of the changes that the rock has been through. In the folding and crumpling the surface must have been bent into elevations and depressions, and the phyllite folded down into the quartzite, and the quartzite folded up into the phyllite. This is probably the reason why we at times find the quartzite in the midst of the phyllite, as we do just west of the bridge at Bloomingdale, in the railroad cutting. If then the surface of the earth had been cut down to a level plain, still the phyllite would be of varying thickness because of this interfolding of the two. Because of the inequality in the erosion the problem becomes still more complicated to estimate the thickness of the overlying phyllite. In but few localities are we able to give any definite idea of its exact thickness. Where we crossed the phyllite in going from Dodge Park to North Park, it is doubtless thin, not more than fifty feet at the most, more likely twenty-five feet. In general we may say that the thickness of the phyllite may be expressed in hundreds, rather than thousands, of feet; in other words, it is comparatively thin.

Age of the micaceous quartzite.

Before leaving the quartzite we must attempt to put it in its proper place in the historical series. In studying this quartzite we have found it intimately associated with the Carboniferous phyllite, interfolded with it so complexly, frequently, that the two cannot be represented separately on our map, because of the smallness of the scale. The quartzite extends alongside of the phyllite throughout the extent of the latter, and does not extend to any distance beyond it at the end. The degree of crystallization appearing in the quartzite is just about the same as that found in the phyllite. There is no marked unconformity between the two so far as can be made out, though in a region of such complex folding and crumpling, where frequently the only structure to be made out is that due to pressure and crystallization, it is quite possible that there may be a minor unconformity which has not yet been determined. Taking into consideration these facts and comparing the quartzite with the neighboring crystallines, it seems best to consider the quartzite as belonging to the same age as that to which the phyllite belongs, though, as it occurs beneath the phyllite, it is, of course, a little

earlier or older. Because of the close relationship of these two rocks in position, and because of the common changes of folding and recrystallization through which they have passed, we conclude that the quartzite, like the phyllite, belongs to the Carboniferous.

CHAPTER III.

Granite of Millstone Hill.

A hill of granite.

In our study thus far, we have gone around Millstone Hill. Let us now ascend this hill. It makes no difference on which side we begin the ascent, we shall find the encompassing quartzite giving place to the granite in the upper part of the hill. On the south side the granite is met at the very base; on the east side the granite appears in the grounds of the State Lunatic Asylum, and extends nearly to the foot of the hill between there and the coal mine; on the north side the ledges are well covered so that little of the granite is seen, and that not as far north as the coal mine; on the west side, the quartzite extends well up on the hill in the vicinity of the pond on Green Farm, and, farther south, in East Kendall street and the neighboring streets; thence south the ledges are well covered until those of Normal School Hill, which are of granite, appear. These last are simply a part of the great granite mass of Millstone Hill, and we may think of the quartzite as being at the base of this hill in East Central street. So, ascending the hill in any direction, we shortly meet the granite which constitutes the great mass of this hill.

This rock may be best studied in the quarries at the top of the hill. The extensive quarrying has exposed broad areas of the granite, and the unweathered rock is ready for our study. It is well for us to trim out a rectangular piece, four inches by three, as a typical specimen.

Description of the granite.

This granite is very different from the phyllite or the quartzite. It frequently presents, on weathered surfaces, a very rusty appearance; has a massive structure; is wanting in foliation or lamination; is cut by fissures or cracks, called joints, in various directions into irregular, angular blocks. Looking now at the fresh surface of the specimen we have trimmed, we see the rock is of a light grey color, and of a medium

coarse, granular texture. The grains vary greatly in appearance, so let us study each kind by itself, constantly using the hand magnifying glass. As we move the specimen in the light, numerous bright, shining, smooth surfaces flash. These are cleavage surfaces, and indicate the crystalline structure of this mineral, and also of the rock. This mineral is white in color, porcelain-like in lustre, and evidently makes up a considerable part of this rock. It is feldspar, and generally orthoclase or potash feldspar. If, however, we carefully examine many of these cleavage surfaces under the glass, we find, now and then, one crossed by many fine, straight, parallel, hair-like lines. These are really fine, smooth grooves or ridges in the cleavage surface, and are formed by very thin plates, with slanting edges, placed in succession, so that the slanting edges either slope towards each other, producing a furrow or groove, or away from each other, producing a very fine ridge. This arrangement is due to the crystallization, and is characteristic of the lime and soda bearing feldspars. The orthoclase feldspar never presents these striations on its cleavage surfaces, whereas the plagioclase or triclinic feldspars frequently do. We therefore conclude that this granite of Millstone Hill contains principally orthoclase feldspar, together with a much smaller amount of plagioclase feldspar.

Feldspar, monoclinic and triclinic.

Quartz, smoky, blue and amethystine in the granite.

The next mineral is clearly distinguished from the porcelain-like feldspar by its glassy lustre, by its smooth, irregular surfaces resembling the surfaces of broken glass particles, and by its smoky color. On searching carefully, examining one after another of these glassy particles, we may find some having a decided blue, and others having a faint amethystine tint. If, perchance, we are examining a somewhat weathered surface, we may find almost every one of the glassy particles blue instead of smoky; within the rock, however, where the weathering has not gone, more of these particles are smoky. It is thus evident that the weathering, generally, if not always, produces the blue color in this glassy mineral. It may be that the substance producing the smoky shade is oxidized by the oxygen of the air to a substance of a blue color. What this substance is, has not been determined, but from the somewhat abundant occurrence of the metal manganese in this rock, we have been led to suspect that this metal has something to do with the development of this blue color, frequently amethystine, in these weathered

surfaces. The glassy mineral is quite generally distributed in somewhat rounded particles, each particle a distinct individual, not a mass of granular grains, as might result from crushing. This mineral we immediately recognize as quartz, which is frequently seen in mineral veins in six-sided prisms, terminated by six-sided pyramids. In fact if we examine many of these quartz particles in the midst of the granite, we shall be constantly reminded of these six-sided prisms or pyramids by the cross-sections presented where quartz particles were broken off. By long searching we may find a little, sharp, six-sided pyramid projecting from the rock surface. It is a crystal of quartz in the very midst of the granite. But much more frequent than these regular crystals, we find isolated, more or less rounded, particles of quartz included in feldspar. These have been called anhedra, because lacking the definite shape of perfect crystals. Breaking away the feldspar around them, we see that they have a dull, etched surface like the surface of ground glass. Occurring in this way, this quartz shows that it did not crystallize later than did the feldspar, but either before or along with the latter; while the irregular coarse quartz filling the spaces between the feldspar particles solidified after the feldspar crystallized, and hence filled the spaces then remaining. We may then divide the quartz into, as it were, two generations. But in this we are anticipating a subject about which we shall have more to say in connection with the occurrence of the granite here. The second abundant constituent of this rock is, then, quartz or silica.

Quartz crystals in the granite.

On examining the rock carefully, especially under the glass, we notice, here and there, but nowhere abundant, small black particles made up of little black scales, shining brightly with a submetallic lustre. This mineral is biotite or black mica.

Biotite in the granite.

But while searching for these black particles, in which we may see the scales distinctly, we must be on the watch for other particles, if perchance there be any. We may observe small particles of a slight greenish or brownish color, made up of many thin sheets, standing on edges and pressed tightly together. We may pick these sheets apart, and then we see nearly colorless scales resembling the biotite scales, except in color. This is another mica, muscovite by name.

Purple fluor spar in the granite.

Before this, in our careful searching, our attention has been attracted by little violet, or purple, colored particles. These are not distributed regularly or abundantly; and we may not find even a single one on the surface of some good sized specimens, but, sooner or later, we shall see such a particle, as the light strikes it, bringing out its color. If the particle is large enough to test, we find it quite soft, so that it is easily scratched by the knife. This is fluor spar, and this mineral will be mentioned in another connection, before we are through with this hill. Its occurrence here will help us to understand its occurrence in the other manner noted beyond.

Of the five minerals found in this rock evidently the first two are the essential ones on account of their abundance, making up, as they do, probably ninety-nine hundredths of this rock; but the micas we shall also consider as important, though not abundant, while the fluor spar we may think of as accidental. All these minerals are crystalline in structure, and as they constitute the grains of the rock, we may describe the rock as of a wholly crystalline, granular texture.

Moreover in our observations, while we note many joints and fissures running in various directions, we see no banding in the arrangement of these minerals, nor any foliation, nor any tendency of the rock to break along certain planes, because of the parallel arrangement of certain minerals. The rock is perfectly massive. All of these characteristics indicate that we are studying a granite. But if it is really a granite, then it is an eruptive rock. In this it differs from the rocks hitherto studied, as they were sedimentary, and afterwards recrystallized into their present condition. When we say that the granite is eruptive, we mean that, in the form of a molten rock-mass, which we may call a magma, it rose from some greater depth, into its present position, and there solidified, crystallizing as it did so, into this massive, crystalline rock. But if this rock thus came into its present position, there are certain facts that we may reasonably look for as confirming this idea. Molten rock rising in this way from beneath must cause more or less disturbance in the neighboring rocks, either melting its way into them, or moving them, or breaking them and inclosing fragments of them, or forcing its way into fissures within them, or changing them because of its contact with them.

Proofs that the rock of Millstone Hill is granite.

Radiating granite dikes wanting.

We will, then, in our study look for these facts. We will first look for fissures in the neighboring rock into which this molten rock may have flowed, and there solidified. These, if there be any, will radiate from the central mass; and hence are most likely to be found near where the granite and neighboring rock come together. Unfortunately for us in this study, the bordering line is generally covered by glacial material, and there is but a limited area where we are able to see these rocks near to each other. This is best seen in the vicinity of East Kendall street. Even here the actual contact is concealed. Nevertheless we are able to determine that the bordering line between the two is not straight, nor a regular curve, but is rather a zigzag line. Though this is true, we do not find any place in the quartzite where the granite has flowed into a fissure and there solidified. However, as the surface material is removed from this region in the laying out of new streets and in the digging of cellars, it is quite probable that such may be found. We are, then, forced to look for other facts to confirm the idea that this rock was in a molten condition when it came into its present position.

Disturbance of neighboring rocks.

We therefore seek for evidence showing that the neighboring rocks have been disturbed. It is not necessary to seek far. It has been pointed out that the laminae of the quartzite in East Kendall street strike or point directly against the granite of Millstone Hill. Over on the other side of the hill the quartzite again appears, but leaning against the hill; that is, the laminae of the quartzite rest on the granite instead of striking against it. These facts we have illustrated in Figure A. But the quartzite on one side of the hill is a part of

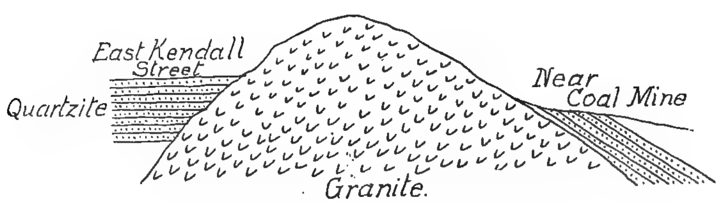


Figure A.

the same formation of which the quartzite on the opposite side is a part, and the laminae of one must be joined with those of

the other. But before we try to do this we must bear in mind that this area has been subjected to great erosion, so that a vast thickness of rock has been removed from above those which are now at the earth's surface. The quartzite now appearing at the surface was formerly covered by a considerable thickness of phyllite. Moreover this Millstone Hill area is not isolated, but is part of quite an extensive anticline which we have already traced from Oakdale, south, to this region. To connect the laminae of the quartzite on opposite sides of Millstone Hill, we must then build up the anticline out of the material that has been removed by the erosion, restoring the quartzite and phyllite above the granite. But in doing this it is necessary, not only to fold the laminae, but also to warp them so that those almost vertical in East Kendall street may join those dipping to the northeast near the coal mine. The relative positions of the three rocks, granite, quartzite and phyllite, before erosion removed any, and the possible shape of the fold, we have tried to illustrate in Figure B.

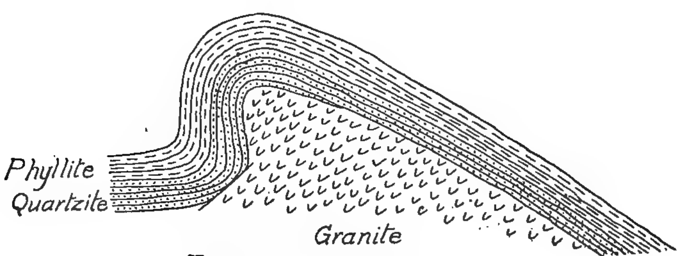


Figure B.

But this folding and warping of the rocks are not the only evidence of disturbance in this region. We have already pointed out how the laminae of the quartzite wrap around the northern end of Millstone Hill, indicated by the change of strike; we have also pointed out that this curving in the strike may be noticed as far away as in the Lincoln street area, where there is a change in the strike from thirty-five degrees east of north to fifty degrees east of north observed in passing down the hill. The meaning of this is that there was sufficient pressure exerted against this rock either to warp the beds of the quartzite around the mass of crystalline rock of the hill, or else to develop in the quartzite a new structure curving around the same, and thus indicating a pressure normal

at all points to this curve. Such a pressure would more likely be from within outward, than from outside towards the centre.

But the warping and rearrangement of the particles producing a curvature in the structure, did not take place without a severe breaking of the rock, and this breaking is an added evidence of disturbance. It was pointed out that the quartzite in the Lincoln street area showed a network of very fine quartz veins; that in the coal mine area the quartzite presents the same, and that the rock of the coal mine has been broken, and then the fragments in part cemented by glassy quartz. All these facts indicate a shattering of the rocks in the area bordering this hill; and the cementing of these fragments by glassy quartz points to the work of hot waters carrying silica into the fine cracks and crevices, filling them and making the rock whole and strong again. Putting all these facts together—the hot waters, the shattering, the new structure or warping—they indicate a disturbance exactly according with the intrusion of a heated rock mass from beneath up into the quartzite and schist.

Inclusions of phyllite in the granite.

But we are not obliged to stop here in our proof of the way in which this crystalline rock of Millstone Hill came into its present position, though perhaps we might be reasonably sure with the evidence already given. If the quartzite and phyllite, at greater or less distances from the hill, were broken and shattered, then the rock nearer and resting on the crystalline rock must have, in all probability, been also broken into larger or smaller fragments; if the crystalline rock, in a molten condition, came into contact with these fragments, it is quite probable that some fragments of the phyllite and quartzite became included in the molten rock, and may now be found in the midst of the crystalline mass.

With this idea in mind let us search, if, perchance, we may find such. The best place in the hill for us to search is the quarries, for there broad areas of the rock are laid bare. In the western part of the large quarry, where the quarrymen have not recently worked, we find a thin band of rock, evidently not the same as the rock of the quarry and, for this reason, not disturbed by the quarrymen. This band is but a few inches thick, but many feet in length; it extends about twenty-four degrees west of north, and dips to the east, about sixty-seven degrees from a horizontal position. The rock is soft, of a dark slate color, and

thinly laminated. The laminae are not always parallel, because small blocks within the band have been moved out of the general parallel position, and in these the laminae are at various angles with the laminae in the remainder of the band. In other words, there has been a breaking of the rock within this band into fragments, in places, and these fragments have moved out of their former positions, producing a breccia. The surfaces of the laminae show, in general, a fine folding or crinkling, resembling that so characteristic of the Worcester phyllite. In fact, so close is the resemblance of the rock of this band to the neighboring phyllite, which we have studied in the first chapter, that fragments from it, placed beside some from the railroad cutting near Bloomingdale, might be thought to have come from the same ledge. Moreover the contact between this phyllite band and the crystalline rock on either side is a contact of fusion—not of faulting nor of sliding of one over the other—just such a joining of the two as would result from a molten rock solidifying in contact with, and attaching itself to, another rock not molten, as the molten rock cooled. From this study we are obliged to conclude that phyllite fragment or band must have been included in the crystalline rock when the latter was in a molten condition. While the phyllite was not so affected by this contact with heated, molten rock but what it is easily recognized, the crystalline rock, for quite a distance on either side of the phyllite, is dark in color, as if the molten rock had absorbed coloring material from the included phyllite.

Inclusion of micaceous quartzite in granite.

Moreover, if we go to the quarry back of the State Lunatic Asylum, whence rock was obtained for those buildings, we may find another inclusion, in the central part of this quarry, consisting of a band of rock distinct from, and unlike the crystalline rock. This band is from six inches to a foot in width, and extends westerly into the hill. The rock of the band is thinly laminated, of a light grey color, and finely granular in texture. It also contains some mica in brownish scales between the laminae. In addition this rock has a distinct banding parallel to the lamination. We immediately recognize it as a micaceous quartzite, and so closely does it resemble much of the Carboniferous quartzite already studied, as to leave no doubt that it was derived from that. But its contact with the neighboring crystalline rock is a contact of fusion. Then here, too, we are forced to believe that this fragment of quartzite became included in the crystalline rock when the latter was a

molten mass. Here, also, the crystalline rock was apparently more affected by the contact, for, on either side of the inclusion, the rock differs in appearance from the normal crystalline rock. There is a like effect where the crystalline rock and quartzite are near to each other in East Kendall street—the granite suffered the greater modification.

These inclusions of phyllite and quartzite, together with the other facts before considered, make clear to us, that the phyllite and quartzite were in this region before the crystalline rock, and are then older in a geological sense; and that the crystalline rock was in a molten condition when it came into its present position. This crystalline rock is, then, since it is composed of the minerals already described, a granite. We may call it a post-Carboniferous granite in the geological series.

The granite of Millstone Hill solidified at some depth beneath the surface.

The shattering of the rocks, already described and so noticeable about Millstone Hill, may be made use of along another line of thought. So far as is known, molten rock does not solidify in the form of granite at the surface of the earth, but in the various forms of lava seen in connection with volcanic activity. For molten rock to solidify in the form of granite, it must do so slowly, giving time for the various minerals to form and crystallize, and these conditions prevail more or less deeply within the earth. So that, whenever we see granite at the surface of the earth, we rest assured that it has not always been there, but is now seen at the surface because the rocks that formerly covered it have been removed. In looking at the granite of Millstone Hill we may be sure that a greater or less thickness of quartzite and phyllite has been removed from above it, so that we may build up the whole surface of the earth around to a considerable height above Millstone Hill, if we would go back to the time when this molten rock mass came into its present position. It then becomes an interesting problem for us, if possibly we can solve it, to determine the depth at which this granite solidified. The shattering of the neighboring rocks may help us along this line of thought.

Possible method of measuring the depth at which the granite solidified.

Let us think of a cubic foot of rock one hundred feet beneath the earth's surface. It is evident that this cubic foot of rock supports the column of rock above it. This column of rock is pressing down on it. Or if the cubic foot of rock is one thousand feet beneath the surface, it is under still greater pressure.

Whatever its depth, it is under the pressure due to the superincumbent rock mass. This pressure may become so great as to exceed the strength of the rock—so that the outside pressure forces the particles of the rock mass together more firmly than does the cohesion between the particles hold them together. Under these conditions a rock cannot break so as to produce fissures and cracks, the external pressure would cause the rock mass to yield by crumbling or crushing or flowing. The rock particles must move one on another; they cannot move away from each other as they do in forming a fissure or crack. If then the yielding of any rock during a disturbance produces cracks or fissures, it is evident that the rock cannot have been at a depth so great that the pressure from the superincumbent rock mass exceeded its strength. When this quartzite around Millstone Hill was shattered, producing those many fissures and cracks now filled by quartz veins, it was not under pressure greater than its strength. When the graphite deposit was shattered, it also was under pressure less than its strength. When also the phyllite, now inclosed in the granite, was broken into fragments producing a breccia, it, too, was under pressure less than its strength. These rocks are not all of the same strength, the phyllite and graphite are much weaker than the quartzite. Evidently these rocks could not have been so deep in the earth when this fracturing took place that the pressure from the superincumbent rocks exceeded the strength of the weakest of the shattered rocks. The phyllite is probably as weak as any of these rocks, and being included in the granite, promises to give us the most definite solution of the problem. Without an exact determination of its strength, it is impossible to tell exactly how deep it must be in the earth to have the outside pressure exceed its strength—where it could not break into fragments. We may however come quite near to this. Prof. Van Hise[1] says in this connection: "In the case of a soft shale, but a small thickness of superincumbent strata, possibly 500 meters or less, may prevent any considerable fractures and crevices from forming." While the phyllite may be more resisting and stronger than what is meant by soft shale, still if we multiply the five hundred by two or three, the depth will be, at the most, a few thousand feet. If then we think of the granite as having come into its present posi-

[1] Sixteenth Annual Report U. S. G. S., Part 1, p. 589.

tion at a depth not exceeding four or five thousand feet, we cannot be far from the truth. That this conclusion is approximately correct is confirmed by other considerations. Many granites give evidence of having been subjected to great pressure after solidification because the quartz and feldspar particles are reduced to fine, granular masses as the result of crushing. Along with this crushing there is developed more or less of a foliated structure within the granite, because of a mechanical rearrangement of the mineral particles. In this granite of Millstone Hill there is neither the granulation from crushing nor foliation from great pressure, except in a very narrow zone bordering some trunk joints specially noticeable in the cliff in the eastern part of Normal School Hill. The local crushing and foliation there seen are undoubtedly due to the movement of these huge blocks of granite, one upon another, and the effects of this motion are only superficial and do not in the least contradict our conclusion. Another consideration that confirms the conclusion in regard to the small depth of this granite beneath the earth's surface is the fact that early in the history of this granite huge cracks or fissures, as we shall later explain, were formed through the mass of the granite. These were formed probably soon after the granite had solidified. Now, that cracks and fissures should form through the granite, indicates that it was not so deep within the earth that the outside pressure from the superincumbent rocks was sufficient to keep these fissures from forming. Hence we may conclude from this, that this granite was not a very deeply buried granite. While these other considerations do not indicate with definiteness the shallowness of this granite within the earth, they confirm, or at least do not contradict, the conclusion drawn from the brecciated phyllite found within the granite. Thus it is, by the attending phenomena, that we may measure the original depth of this granite, and determine the thickness of the rock mass since removed by erosion.

Aplite dike in granite of Millstone Hill.

In this discussion in regard to the relation of this granite of Millstone Hill to the surrounding rocks, we have been led away from our study of the rock of the quarry. Following the road leading along the western side of the quarry, as we approach the northern part of the quarry, we notice what seems to be a high wall extending approximately northwest by southeast almost continuously across the quarry, and rising to different heights above the floor of the

PART OF THE APLITE DIKE LEFT STANDING ABOVE THE NEIGHBORING ROCK OF THE QUARRY, MILLSTONE HILL.

quarry, where highest, perhaps twenty-five or thirty feet.[1] In width it also varies, at the southeast end being about thirteen feet wide, and in other parts seventeen to twenty. We see that this wall is what the workmen have left in quarrying, and its upper surface shows us the former level of the rock surface in the top of this hill. From this we may gain an idea of the large quantity of rock that has been removed from this hill by the quarrymen. But the question naturally rises why the workmen left this wall while removing the adjacent rock to the base, leaving a vertical surface on either side.

Aplite dike.

On examining the rock of the wall and comparing it with the rock of the rest of the quarry, the answer is quickly found. It is frequently lighter in color, being nearly white; it is much more finely granular in texture, and is cut by joints or cracks so that it breaks into small, angular blocks. It was left, evidently, because it was not so well fitted for use as a building stone. Let us examine this rock more carefully to determine of what minerals it is composed, and discover, if we may, what may be its relation to the granite already studied. First we examine a specimen which is almost white. We easily pick out the feldspar by the smooth, shining, porcelain-like cleavage surfaces glistening in the sunlight. We examine a number of these under the magnifying glass, and, now and then, see one having the fine straight lines indicating a triclinic feldspar. We also recognize the quartz, though in finer particles, by its glassy lustre and want of cleavage, looking very much like fine pieces of broken glass. These minerals we recognize as the essential constituents of this rock. In addition we may find, now and then, as we move the magnifying glass around in our examination, a little cube of a brassy color and metallic lustre. Iron pyrites is also distributed in this rock. The lighter variety of this rock is then composed of feldspar and quartz, is of a crystalline, granular texture, and is perfectly massive without foliation or banding. These are characteristics of the rock called aplite. But this rock has another phase slightly different. It has a decided grey color. Under the magnifying glass we see that this color is due, in large part, to the abundance of smoky or grey quartz and feldspar, and in part to another mineral in fine

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[1] Since the above was written this wall has been largely removed for road material.

black particles, probably biotite. We see that this aplite is closely related to the granite as far as the minerals constituting it are concerned, but it is finer in texture. Continuing our study, we search for the border line between the granite and aplite, and near the northwestern end of the wall find a place where we may clearly see the granite and aplite meeting or in contact. At this place there is not a blending of one into the other, but a well defined line between coarse granite on one side and fine aplite on the other. There is not however any break or crack or fissure in the rock along this line. It is quite evident that this union or joining of these two rocks could not have been made when both were solid. It is clearly a contact of fusion. It must have resulted from at least one of these rocks being in a molten state and solidifying on the other. The relation of these two rocks will appear more clearly if we now study rock of the same kind, as it occurs in the southern part of Millstone Hill, south and east of Bell Pond. Here the aplite frequently occurs in the midst of the granite, in bands fifteen feet or more in width, and extending in various directions. On the east side of the pond, extending down under the water, is the most instructive one for our present study. Here we may follow the aplite bordered by granite on either side for a distance of twenty feet or so, in a northwesterly direction, the aplite being only two to four feet wide. As we approach the edge of the water we observe a branch from the aplite extending out into the bordering granite. The dividing line between the granite and aplite is so clearly defined that we may draw a pencil along it, yet there is no fissure or crack. This narrow band of aplite with a branch extending out into the bordering rock can be nothing but a dike. Reasoning from this we conclude that all the other aplite bands are also dikes. There are many of these, but no other one is so convenient for study as the large one up in the quarry.

Formation of aplite dikes.

These dikes have an interesting story to tell us of what has taken place since the granite came into its position, and solidified beneath the upfolded quartzite and phyllite. After the solidification of the granite (but how long it is not possible to tell, though, geologically speaking, probably only a short time), the granite was broken and rent by fissures, some fifteen to twenty feet wide, others but a few feet in width, extending in various directions without uniformity as far as has

been noticed. These fissures were deep enough to reach down to molten rock, probably a part of the granite magma that had not yet solidified; and up into these fissures flowed more molten rock, completely filling them. As this molten rock solidified, it became attached to the granite without crack or fissure between, forming the fusion contact now seen. By cooling more rapidly than did the granite, it came to have a finer granular texture.

Inclusion of phyllite in aplite.

Let us now return to the large dike in the northern part of the quarry. When we have gone about one-third of its length from the northwestern end, where the contact of the aplite and granite is very distinct, we find a place where there is, in the midst of the aplite, and separated by it from the granite, a thin band of rock quite different from either granite or aplite. This rock is of a light slate color; the material of it is arranged in thin fissile laminae; it has a smooth feel, and presents in places a finely corrugated or wrinkled surface. In fact this rock bears a close resemblance to the phyllite of the surrounding area, and is evidently a small fragment of it inclosed in the aplite. But we may rightly ask how it got there. We may think of it as a fragment of the phyllite which fell into this fissure as the granite was rent asunder, and became surrounded by the uprising molten aplite, and there held, as the rock solidified, until the work of the quarrymen exposed it to view. This included phyllite is a striking confirmation of the idea already expressed, that the phyllite once extended over the top of Millstone Hill, for, unless this were true, certainly none of it could have fallen into the fissure.

Dark lines in the aplite.

As we go along we see many cracks or fine fissures running through this aplite in various directions. These are so numerous in places as to produce almost a network. It must have been subjected to great tension, perhaps from cooling, at some period which has produced these. Many of these have since been filled with fine glassy quartz which has been brought in and deposited there by water. Frequently these cracks are bordered on either side by a darker grey band. This effect was evidently produced by material, also brought into these cracks by water, which soaked out into the feldspar and quartz, coloring them. Because of this coloring the cracks are very noticeable, and may be observed in other dikes in various parts of the hill.

The oxidized porous border of the aplite.

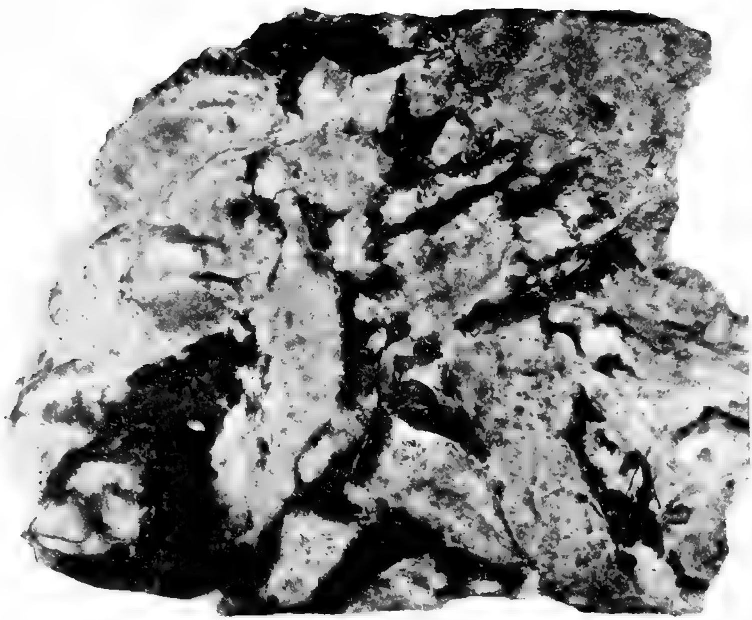
As we approach the road crossing the aplite dike near the southeast end, another fact attracts our attention. In the south part of the dike where it comes in contact with the granite the rock is peculiar. It is very rusty, and is not compact, but made up of thin sections, bent and broken and separated by thin, flat cavities. The surfaces of these cavities are covered with yellow iron rust. Under the magnifying glass we find these thin sections to consist of fine, granular, glassy quartz of sugary whiteness. Evidently these flat cavities have been formed by the dissolving out by water of some mineral, which was evidently oxidized as it was dissolved, and the iron in it became iron rust forming a lining to the cavity. What this mineral was has not been determined, as this dissolving out and oxidation have gone as deeply as we are able to dig into the rock. We can only conjecture as to what it was. It may have been a carbonate containing considerable iron; and this is quite probable, as in another part of the quarry we find such a carbonate at the present time in the process of solution and oxidation. Possibly the mineral was a sulphide of zinc containing much iron, for we find such a sulphide in other parts of the quarry.

Quartzite in aplite.

But we return to the study of the rock itself. By breaking out many pieces we find a part where this white, sugary quartzite is compact, without cavities, and is in contact with the aplite. Here we see that the aplite has attached itself to this quartzite just as it did to the granite, and so we are led to believe that this white quartzite is a fragment from one of the neighboring rocks. Possibly it is a fragment from a white variety of the carboniferous quartzite, or possibly it is a quartzite fragment that was included in the granite before the aplite filled this fissure. Certain it is that this quartzite closely resembles a much earlier quartzite found at the surface of the earth far to the east, but which probably extends under this area at a considerable depth. Possibly, then, it is a fragment from that, brought up in the molten granite as the magma rose through the underlying rocks.

Aplite breccia.

If we are careful here in our search, and break out many fragments for examination, we shall find, between this rusty quartzite and the compact, finely grained aplite, still another rock which at first seems to be a confused mixture of the two. On closer examination, however, we



Aplite Breccia from Millstone Hill. Original, 7 by 5½ Inches. Light Areas are Aplite Fragments.

are able to arrange the aplite by itself and the quartzite by itself. The aplite is in angular fragments or blocks, frequently an inch or two through. Between these blocks is fine grained, white or rusty, sugary quartz resembling that of the quartzite just described. We immediately recognize the rock as a breccia, for it is made up of angular fragments cemented together. We can see from this, that in this limited region, in some way, during the vicissitudes through which this rock mass has passed, the aplite here was broken into fragments, and then these fragments were cemented together by the granular quartz. But we must acknowledge that this is but the beginning of the complete explanation which we are not now able to give.

Aplite having an odor.

Continuing our study of this dike, we cross the quarry road to where the dike meets the eastern side of the quarry. Here we break off a specimen for examination, and immediately notice a strong, offensive odor. We break off another piece at a different place, and again the odor is perceived. After trying the rock in several places with the same result, we conclude that the odor belongs to the rock here, at least, for we have not observed it elsewhere in the aplite. To what this odor is due we do not know, only that we have perceived this odor coming from other rocks when broken, especially from quartz; and it is possible to find smoky quartz in this quarry affording, when broken, this same odor. Because of the odor such quartz is called fetid quartz. The aplite possessing this odor may be called fetid aplite.

Beyond the clearing of the quarry it is not possible to trace this dike, and so we do not know exactly how far it extends. Very likely it extends to the eastern side of the hill, and future observations may reveal it, as the covering is removed.

Beryl in the granite.

Having followed the aplite dike across the quarry, we next seek other points of interest presented here. Near the extreme northern end of the quarry, on the right hand side, as we face the north, may be found a small area, a foot or two in diameter, marked by a green color. It is clearly different from the surrounding rock, and it is evidently a crystalline mass. The crystals run together so that we cannot obtain individual crystals. The mineral is not clear and transparent, only translucent. It is very hard. Fine fragments may be picked up, and now and then one will show more or less clearly a six-sided

prism, and tell us that this mineral is beryl. At another point a little farther south in the quarry wall occurs a similar area of beryl. In like manner, at other points, probably, this mineral may be found distributed in these isolated masses within the granite. These indicate that about these points the beryl, which was distributed through the molten magma, crystallized, and must have crystallized before the other minerals, because the other minerals are not included within the beryl mass.

On the left hand side of the northernmost point of the quarry is another locality quite rich in minerals. The area is small, being only four to six feet in diameter, and the weathered surface is covered by much iron rust from the minerals within. On breaking into the rock we find it having little resemblance to the average granite. It is of various colors, depending on the abundance of this or that mineral, and frequently the rock is composed largely of a light colored mica, the mica scales having no uniformity of position. The minerals are generally in too fine particles to be studied by the unaided eye. Looking through the magnifying glass we instantly recognize six-sided clear, glassy prisms of a green color. They are perfect and beautiful enough to be used as gems, if only they were larger and could be separated from the inclosing rock. They are crystals of beryl, and are much more satisfactory than the beryl occurring in coarser masses.

Nicely crystallized beryl.

There is also here, perhaps more abundantly than the beryl, a brownish, amber colored mineral having also at times a pinkish tinge. It is distributed in grains and frequently makes up a considerable part of the rock, giving its color to the whole. Upon testing this mineral, it proves to be a garnet, but, unfortunately, is seldom in well defined crystals. By searching we find one having the shape of the rhombic dodecahedron.

Garnet in granite.

Still another mineral observed here is of a black color, resinous lustre, and presents bright cleavage surfaces when broken. This gives tests for sulphur, iron, zinc and manganese, and is, then, an impure sphalerite or zinc blende. Because of its impurities it is more interesting than the pure would be.

Sphalerite in granite.

By searching carefully, especially in that part of the rock decidedly micaceous, we may find a mineral of a dark, bluish grey color, of a bright metallic

Molybdenite in granite.

lustre, distributed in small thin masses which cleave into thinner scales. This mineral is very soft, and, drawn across the page, leaves a mark on the paper resembling that of the pencil. The mark of the former is brighter, especially in the sunlight, and, on closer examination, may be seen to have a slight greenish tinge. On testing it in the laboratory, it gives a sulphur reaction, clearly distinguishing it from graphite. It is the mineral molybdenite. Iron pyrites, known by its brassy color and hardness, is also found here. In fact it occurs so frequently, here and there, through the quarry as to seem hardly worthy of mention.

Purple fluor spar.

But the mineral most eagerly sought here, which gives the greatest pleasure when found, at least to the beginner, is fluorite or fluor spar. This is easily recognized by its purple or amethystine color. It is here distributed in little masses within the rock. Its occurrence here is similar to its occurrence in the granite proper, of which we have already spoken, though here it is in much larger particles.

The area of these minerals an area of segregation in the granite.

Within the area of a few square feet are found all these minerals crowded together, while in other parts of the quarry we may search over large areas without finding even one of them so abundantly. This area is not a vein in which water has deposited these minerals. As far as we can see the rock in which these minerals are is an original part of the granite mass, blending as it does in all directions into the ordinary granite of the hill. This mineral region has evidently been here as long as the granite has, and is in no sense secondary to it. But the explanation of this area is closely connected with the explanation of other facts before noticed, and we will attempt to explain all together. We have considered the evidence that leads us to believe that the granite of Millstone Hill was once a molten mass, and in that condition came into its present position. From this molten mass or magma various minerals crystallized, and in some regions of the granite minerals quite different from the ordinary minerals separated out. We may inquire in what condition these minerals of the granite must have been and what relation they bore to each other in the molten mass.

Rock magma a complex solution.

We may, of course, think of this molten magma as a mixture of various molten minerals,—so much quartz, so much feldspar, so much mica, and so on, each mineral retaining its identity even in the molten mass. A

little thought, however, will probably lead us to another conclusion. Temperature has much to do with chemical action between different substances and elements, and also with the solution of substances in solvents. Certain elements unite at high temperature which will not unite at the ordinary temperature. A common illustration of this principle is seen in the action of charcoal and oxygen. At the ordinary temperature a piece of charcoal may remain indefinitely in contact with oxygen of the air without any action taking place between them; but at a red heat charcoal and oxygen readily unite. The charcoal then burns. Likewise a piece of soft iron and charcoal may remain in contact at the ordinary temperature indefinitely without action, but at an elevated temperature the carbon is absorbed or dissolved by the molten iron. The melted iron is capable of forming a chemical compound or compounds with the carbon of the charcoal. The iron which has thus dissolved carbon is quite a different substance from the same iron without the carbon. Allow the molten iron, saturated with carbon, to cool rapidly, and this carbon remains united with a part of the iron, the whole forming a solid solution; but allow the same iron to cool slowly, and the carbon, in part, crystallizes out from the iron, and appears in little crystals of graphite disseminated through the iron. But even in this case a part of the carbon remains united with the iron, causing the cast iron to be quite different from the soft iron without any carbon. In other words, some compounds and solutions, formed at elevated temperatures, may, by rapid cooling, be preserved at the ordinary temperature; and on the other hand, by slow cooling, may be resolved into quite different substances by a rearrangement of the elements and substances of the molten mass.

Effect of slow cooling on a magma.

The same principle holds in the case of rocks. The molten volcanic rock, cooling rapidly, forms a non-crystalline glass. This possibly preserves the relation which the different substances bore to each other in the molten mass. This apparently non-crystalline mass is really a solid solution consisting of minute crystals that began to form in spite of the rapid cooling; of substances that were in solution and solidified in the midst of their solvent because not allowed time to separate and crystallize by themselves; and of the solvent that held these substances in solution. If, on the other hand, the molten rock mass that solidified into glass had solidified slowly, allowing complex

substances to break into simpler ones, and substances in solution to separate from their solvents, and then the solvent or solvents themselves to crystallize, the cooled rock mass would have become a wholly crystalline rock instead of a non-crystalline glass.

Effect of pressure on a magma. But temperature is not the only agency that may influence chemical action and the solution of substances in solvents. Pressure, more or less great, will force certain elements into chemical union which would not unite by simple contact under the ordinary pressure, and will force substances into solution which would not otherwise dissolve. In like manner pressure will keep together the elements of certain compounds and will keep in solution substances which would separate under the ordinary pressure. In other words complex compounds and solutions may exist under considerable pressure, which would break up, or tend to break up, under reduced pressure.

Crystallization of the magma. Let us now apply these principles to the molten mass of rock which finally became the granite of Millstone Hill. It was at a temperature more or less high so that all the minerals within its mass formed one complex solution; but this was not at the surface of the earth, it was thousands of feet beneath the surface, at least before it rose into its present position. Being thus deep within the earth, it must have been under correspondingly great pressure. Under this pressure a complex solution might be possible that would not be possible under less pressure with the other conditions the same. Then as the molten rock mass rose towards the surface of the earth, the pressure decreased more or less slowly, depending on the rate of the upward motion. With this decrease of pressure we may think of a slow cooling of the molten mass taking place—conditions which would be favorable to the beginning of the separation and crystallization of simpler minerals. This crystallization took place in the midst of a liquid where there was nothing to interfere with the formation and growth of perfect crystals, and so these first minerals formed in well defined crystals.

Moreover, as this crystallization took place, the remaining molten magma became simpler by the amount of substance removed, and was then capable of holding together under the changed conditions of temperature and pressure, and so the crystallization stopped, only to begin again when the conditions of temperature and pressure again changed so that this still complex solution of the

magma could not hold together. When the final crystallization took place, as the result of the slow cooling of the molten magma inclosed in the cooler surrounding strata, then the crystals and crystalline aggregates, before formed, were inclosed, here and there, wherever they happened to be, in the solidified mass.

Thus may we explain the occurrence of quartz crystals which may be found in the mass of the granite, and the beryl, and garnet crystals distributed through the granite, either in single crystals or in crystalline aggregates. They were the first substances to crystallize out in the molten magma, and were formed of material which could not, in the changed conditions of the magma rising through cool strata to regions of less pressure, remain in solution in the complex molten substance.

Ankerite in granite.

There is still another mineral region in the southern part of the quarry. You will be assisted in finding it by the fragments of rock lying about having a resemblance to cinder. These fragments are dark in color, very porous, and the cavities are lined with a black coating. On breaking into one of these you may find the undecayed rock, and this will assist you in finding the same rock in the ledge near by. There will be little difficulty in finding it in the ledge, as it occurs in quite a large area. You will then see that the mineral, which so easily decays, first turns to a rusty color, as it begins to be acted on by the agents of the air, forming brown blotches on the surface of the rock. Within the undecayed rock you will find this mineral in crystalline, granular masses, varying in color from dark bluish grey to pure white. It is soft, and effervesces with hydrochloric acid, showing that it is a carbonate. It contains, as is shown by analysis,[1] 85.13% $CaCO_3$. It is not the simple carbonate of calcium; it also contains iron and manganese carbonates. We may think of it as calcite in which a considerable part of the calcium is replaced by iron and manganese. It may be the mineral ankerite. From this it appears that manganese is quite widely distributed through the granite of this hill. This mineral area does not have the appearance of a vein but simply a region within the granite. The granite probably derived this carbonate from the phyllite or the quartzite when, as a molten mass, it rose and came in contact with them, for in them, as we have already pointed out, there is a similar carbonate.

[1] Analysis by Harold Lane.

Vein minerals. Quartz crystals.

In addition to these areas, minerals may also be found in veins within the granite. At some time there were formed cracks or fissures; through these water has soaked during long periods of time, bringing in and depositing various minerals. In such veins may be found quartz crystals. These have been noticed especially on the south surface of the large aplite wall near the western side of the quarry. These crystals are sometimes glassy, and sometimes milky, quartz, and show the six-sided prisms terminated by the six-sided pyramids. We have been told that in some parts of this hill, while digging cellars, workmen have found quite thick veins of quartz containing large crystals, and the workmen supposed these were diamonds and filled their dinner pails with them. These quartz crystals indicate the action of hot water bringing in and depositing quartz in the fissures of the rock.

Green, purple, white fluor spar.

On the surface of this same wall may also be found fluor spar, green, purple or amethystine, and colorless or white. But the fluor spar is by no means limited to any one part of the quarry. Wherever the men are at work, especially in the deeper parts of the quarry, the blocks of rock will frequently be found coated, to a greater or less extent, on surfaces adjoining fissures, with a very thin layer of the purple fluor spar. Nor is it difficult to explain whence this fluor spar comes. In describing the granite we pointed out little particles of fluor spar distributed through its mass. These particles are dissolved by waters soaking through the granite, and the fluor spar from these is carried into the cracks and fissures, and there deposited as a coating on the sides. Through the agency of the soaking waters this mineral is thus concentrated, and hence occurs in much larger masses in these veins.

Iron pyrites.

Along with the fluor spar, iron pyrites occurs in thin masses constituting a part of the veins. It, too, has been concentrated through the agency of water.

Dark grey variety of the granite.

At the beginning of the discussion in regard to Millstone Hill, a description of the normal granite was given. That description does not apply to all of the granite. In some areas the granite is of a dark grey, instead of a light grey, color. This is due to the dark color of both the quartz and much of the feldspar. This quartz is of a very dark smoky color, not infrequently black, while much of the feldspar

is also dark grey. Judging from the number of striated surfaces, there is no more of the triclinic feldspar in this dark feldspar, than there is in the white, so that we cannot attribute the change of color to a change in the feldspar. On studying the occurrence of this dark granite, we notice that it is most frequently found either bordering the phyllite inclusions or bordering cracks and fissures. This observation leads us to suspect that the darkening of the granite is due to the taking up of material from the phyllite. This took place, partly, directly from the phyllite inclusions, and partly from waters that had been in contact with the phyllite and had become impregnated with matter from it, which soaked through the cracks of the granite and imparted this matter to the granite, and thus colored it.

Phyllite highly impregnated with solutions from the granite.

In the southern part of the quarry, south and southeast of the carbonate area, is a rock of peculiar appearance. The area in which it occurs is about eight feet in width, and may be traced fifty feet or more in an easterly direction. The rock is of a dark grey color, and shows a trace of foliation producing a cleavage. On such cleavage surfaces the glassy quartz appears in black, shining particles, entirely distinct in the inclosing grey mass. These quartz particles are not crystals, but irregular, rounded masses an eighth of an inch or so in diameter. So distinct are these from the inclosing material that they produce somewhat of a porphyritic appearance. After much thought, and the examination of many specimens from this area, it seems reasonable to consider this rock as a phyllite inclusion in which the phyllite and granite have affected each other to a much greater degree than they did in the case of the other inclusion described in an earlier part of this chapter. Hot liquids, abounding in mineral matter, especially quartz, derived from the granite, soaked into the phyllite, and there the hot solution deposited minerals, changing the phyllite almost beyond recognition. On the other hand, also, matter seems to have been carried from the phyllite into the granite magma, giving to the feldspar and quartz a color as dark as that of the phyllite itself. Why one inclusion of phyllite should be so changed, and another, a few hundred yards away, remain almost unchanged, is difficult to explain. The thickness of the unchanged one will not explain it, as this is but a few inches thick. Possibly the unchanged one became inclosed in the granite magma when dryer, or at a later time, when the magma

A Wall of the Quarry in the Top of Millstone Hill, Showing the Jointing of the Granite.

was somewhat cooler and approaching the temperature of crystallization. But even in this case the granite on either side has the dark color, showing that the phyllite affected it, if the granite did not affect the phyllite.

Jointing of the granite.

There is another fact that has attracted our attention as we have gone about the quarry. The granite is not in one unbroken mass, but divided into slabs of varying thickness, which are approximately parallel in position, thus constituting, as it were, sheets, one above the other. These sheets do not extend horizontally across the hill, but curve so as to be parallel with the outline of the hill. In the northern part of the quarry these sheets slope down to the northwest at an angle of about twenty degrees. In the central part of the quarry the sheets are approximately horizontal; and in the eastern part, they slope down to the southeast at an angle of about twenty degrees. These sheets are seen to the best advantage in the vertical walls left by the quarrying away of the rock.

These sheets are not of uniform thickness. At the top of the wall, bounding the quarry on the northeast and east sides, these sheets are not more than six inches thick, perhaps even less; and they seem to rapidly increase in thickness so that at a depth of twenty-four feet they are apparently two feet thick. But on careful study we see that this thickening is largely only apparent. Near the surface of the hill every crack and fissure is distinctly brought out by weathering and frost. The former has produced a border of iron rust on either side of every crack, while the latter has enlarged and opened them so that there the rock appears in quite thin slabs. Farther down in the granite, even at the depth of twenty feet, it is seen, on close observation, that there, too, the granite is cut by many cracks which have not yet been so distinctly brought out. Because of this we cannot determine just how great the increase in thickness of the slabs is. The breaking of the granite into these sheets, wrapping over the hill, indicates tension within the mass, and probably this tension was produced by the constant expansion and contraction of the superficial parts of the granite due to the heating of the rock by the sun's rays and the cooling when these are withdrawn.

These sheets are not, however, continuous, but are crossed by many cracks and fissures at various angles, and are thus cut into slabs. These cross fissures are more or less nearly at right angles

to the sheets and may be divided into two classes. The major, or trunk, fissures and the minor. The minor are frequently but a few feet in length and extend in any direction. The surfaces of the granite bordering these are frequently covered by a thin, shining coating of fine greenish mica. Because of the cross cracks, the granite breaks into irregular blocks; and a wall built out of these untrimmed blocks looks as if it had been built after a crazy quilt pattern.

Crushing and production of foliated structure along joint planes.

The major or trunk fissures run down into the granite and are nearly vertical in the quarry. In other parts of the hill they deviate somewhat from the vertical direction. At times they are parallel, at other times not parallel. These are specially marked in the vertical cliff east of the Normal School. Here they strike about northwest, and have a dip of about fifty degrees to the southwest. Here these fissures are parallel. These major or trunk fissures are bordered by a thicker coating of brownish green mica, and the rock surfaces are smooth and polished, and covered with striations or rounded scratches. Frequently also the rock on either side of these fissures has a marked foliated structure; and the granite within these folia is finely granulated, the quartz and feldspar being reduced to a powder. All these facts point to great pressure within the granite mass by which the rock was broken to great depth, as it were, into great cakes or blocks; these blocks rubbed and crushed against each other producing mica-covered and striated surfaces, frequently also grinding the very rock to the depth of several inches on either side to a fine powder and arranging the powdered rock in thin folia parallel to the fissure. As we look at the cliff east of the Normal School it does not require much imagination to see that the granite of this ledge was subjected to great pressure from the southwest until the whole mass was broken into these massive blocks, and these moved, each against its neighbor, grinding and crushing the surfaces. These facts tell us that this granite has not remained quietly inclosed in the surrounding rocks through the ages, while those above were being removed by erosion, finally bringing it to the surface, or rather bringing the surface of the earth down to it.

Weathering of granite.

Another fact noticed, as we study the rock of Millstone Hill, which we should consider before leaving the subject, is the appearance presented by

Cliff of Granite East of the Normal School, showing the Joints by which the Granite is Cut into Angular Blocks.

the rock surfaces long exposed to the air, or bordering the trunk fissures. These surfaces are uniformly very rusty, and frequently black in color. On breaking into the rock we find the black a surface coating, while the rusty appearance extends more or less deeply into the rock, forming a zone frequently several inches in thickness. The rusty color we instantly recognize as that of iron rust. Upon testing the black coating, we find that it gives a decided test for manganese, and will set chlorine free from hydrochloric acid. We therefore conclude that in the black coating there is considerable black oxide of manganese mixed with the iron rust. These oxides of iron and manganese result from the decay of this granite. For ages water has been soaking through the fissures carrying in solution oxygen and carbonic acid from the air, and organic acids from decaying vegetation; this water has soaked into the rock, on either side of the fissures, between the minerals and along cleavage planes; on these minerals the oxygen and acids have acted, taking various elements out of the minerals and leading to the formation of new substances. As this takes place the minerals crumble, more or less, and the rock is weakened. If the rock happens to be within the reach of frost, that helps on the work of disintegration. In this change, iron, which occurs in minerals in the granite, becomes iron oxide or iron rust, and shows by its color the distance into the rock to which the waters have carried oxygen from the air. By such changes this granite slowly crumbles into loose particles of clay and sand. As this change takes place we notice a variation in the thickness of the weathered zone. This zone is noticeably thicker at the corners, and the corners of the inside surface of the weathered zone are more rounded than are the outside corners. This is because the weathering, extending in from one surface, has met that extending in from the adjacent surface, and as a result the corners become less and less angular as weathered zone after weathered zone is broken off. In this way an angular block of granite tends to become spherical or at least rounded.

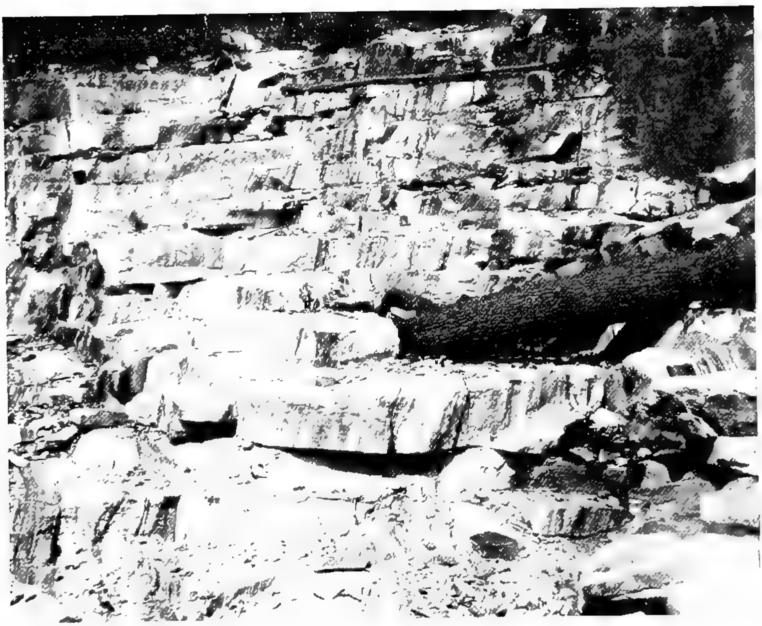
Disintegration due to fluor spar and iron pyrites.

But this granite contains an element of weakness not always found in granites. It contains as we have pointed out little particles of fluor spar quite thickly distributed through its masses, as well as constituting veins in fissures. The granite also contains iron pyrites. As the latter is oxidized, it either forms an acid sulphate or free sulphuric

acid. Either of these, coming in contact with the fluor spar, acts on it, setting free hydrofluoric acid. The latter acts forcibly on the rock minerals around the fluor spar, and causes them to crumble. That this action does take place we were led to believe from the study of one specimen in particular which abounded in fluor spar and iron pyrites. The surrounding minerals had been acted upon by some agent so that they crumbled easily, while the iron pyrites and fluor spar were in part fresh and unacted on.

Summary.

We will now summarize the leading facts brought out in our study of the granite of Millstone Hill. As a molten magma this rock rose from some greater depth in the earth into the midst of the Carboniferous phyllite and quartzite, either greatly disturbing and moving them, or flowing through breaks and under folds that were produced by other causes. But this molten rock did not reach the surface of the earth; it rose to within a few thousand feet of that surface and there crystallized—certain minerals crystallizing before the general solidification took place. Later this granite mass was profoundly broken so that great fissures extended through it in various directions. These fissures were channels into which more molten rock flowed and crystallized, completely filling them, and making the aplite dikes. By the agents of erosion the superincumbent rocks were slowly removed, and the surface of the earth was brought down to the buried granite. But no sooner was the granite uncovered, than the same agents began to work on it, pulverizing it and washing it away to form sand and mud to be deposited as sediments by water. The ice of the Glacial Period also removed an appreciable amount from its mass, and spread bowlders from it over the fields to the south. If only these, together with the finer rock-flour which resulted from the crushing of many other fragments of this granite, could be returned to this hill, its top would be sensibly elevated. Hence it is that the original granite mass exceeded, considerably, that with which we are now acquainted. But we must remember that what we see, appearing only in the top of the hill and not even reaching to the visible base, gives us but a small idea of the real extent of this granite. As it rose from beneath, the direction of its greatest extension is down into the earth. It is impossible to tell exactly how far it extends down, but we risk nothing in prophesying that it extends to a great depth, and that its length and width are small compared with its depth.



WALL OF THE BALLARD QUARRY, NEAR QUINSIGAMOND, SHOWING HORIZONTAL JOINTING AND BANDING RESULTING FROM ALTERNATION OF SCHIST AND GRANITE.

CHAPTER IV.

Bolton Gneiss.

Let us bear in mind that the subject for our study is the rock-floor of Worcester. In this study we have now considered that which underlies the central part of Worcester from the northern to the southern boundary. There remain for our consideration the extreme eastern and western areas beyond the boundaries of the quartzite.

Southeast slope of Wigwam Hill.

That we may begin in this new study at a point where we are already acquainted, let us again go to Wigwam Hill. Instead of studying the top of the hill, let us go down the southeastern slope. A few hundred feet from the Carboniferous quartzose mica schist, we find a ledge which instantly appeals to us as of quite different rock. It is laminated or foliated, but we look in vain for the extreme folding and crumpling so noticeable in the rock at the top of the hill; and this rock is not traversed by any such bands or beds of granular quartz. It has a finely speckled appearance due to white particles inclosed by a dirty, dark grey, micaceous mass. It points seventeen degrees east of north and dips about eighty degrees to the west. Breaking off a piece for study, we find the rock highly micaceous, consisting in considerable part of fine scales of brownish mica approximately parallel to each other. On a surface at right angles to the laminae or folia we see that the white spots referred to are flattened lenses, sometimes of quartz and sometimes of feldspar, while the fine white material is probably a mixture of much quartz with a little feldspar. This rock is a well foliated gneiss. From here the formation of which this rock is a part, may be traced far to the northeast, beyond the bounds of Worcester; to the south also it may be traced many miles, lying, as it does here, just east of the Carboniferous quartzite. This formation constitutes the rock-floor in the extreme eastern part of Worcester. Moreover it is not limited to Worcester in its eastward extension, but may be traced by the ledges many miles to the east, as well

as to the north and south, beyond Worcester. It is of great extent here in Central Massachusetts.

Ballard's quarry near Quinsigamond.

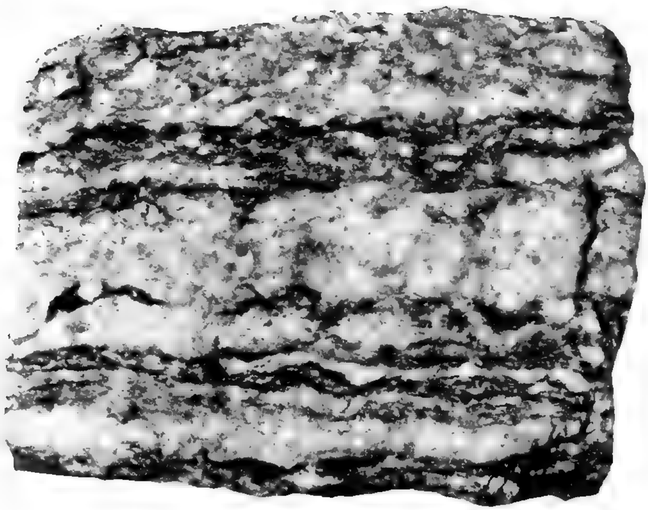
Starting then from Wigwam Hill, we may trace this formation by means of the outcrops appearing in the fields, down to the quarry belonging to the Ballard estate, near Quinsigamond. Here, because of the extensive cut that has been made in it, we may study this formation to the best advantage. Here everything is in sharp contrast with what was seen at Millstone Hill. Everywhere the rock is banded.

The light and dark alternating bands are almost as distinct and clearly cut as are the bands in agate. We may trace these bands across the quarry, except where they are concealed by the quarry road and the piles of quarried rock. These bands are in general parallel, and the direction is approximately the same throughout the quarry, except where there is a local bending or folding, throwing the bands out of the general direction for a short distance. This general direction is twenty-five to thirty degrees east of north. These bands are also tilted up at a high angle, frequently standing almost vertically, having a dip of seventy to eighty-five degrees to the west.

This description will serve to give us a general idea of the rock of this quarry, but there are many interesting facts here presented which will appear only with more careful study. Let us then study the separate bands appearing in the floor of the quarry, beginning in the middle of the west side, and going to the east. We shall thus walk across the edges of the different bands.

Study of the rock of the quarry floor, band by band. Gneissoid granite.

(1) The first band is about twenty-seven feet wide. The rock of it is of a light grey color, of coarsely crystalline texture, and of foliated structure. This structure is due, in part, to the distribution of the black mica in thin, discontinuous sheets; and, in part, to the uniform arrangement of the intervening particles so that their longer axes are parallel to the mica sheets. Both particles and mica sheets are parallel to the general banding of the quarry rock. This arrangement of the minerals gives to this rock a streaked appearance rather than a distinct banding. The minerals, in addition to the mica, making up this rock are feldspar and quartz. The former is recognized by its many cleavage surfaces and its porcelain-like lustre. It is generally pure white in color, but has, now



Gneissoid Granite from Ballard's Quarry, Near Quinsigamond.
Original, 5 Inches by 4.

and then, a slight greyish tint. The feldspar particles vary greatly in size. Some are half an inch or less in diameter, others are three to four inches long by one to two inches wide, and there are all the intervening sizes between these two extremes. Within these feldspar particles may be seen, under the magnifying glass, little inclusions of quartz, rounded in shape, sometimes oblong and sometimes cylindrical and worm-like. The feldspar particles do not show the definite outline of individual crystals, but join, one to another, forming a confused crystalline mass. Now and then a feldspar individual is separated from the surrounding minerals by mica; even then it does not present the outline of a crystal, but is flattened and rounded into the shape of a lens lying parallel to the banding of the rock. The feldspar does not present striated surfaces, and so we conclude that it is all orthoclase feldspar. As we study it thus carefully, we notice that the lens-shaped particles frequently have a rim of finely granular feldspar, the latter a part of the rounded particle, yet having this different texture. If we think of this particle as having been partially crushed, the crushing reaching in but a short distance from the surface, this fine granular rim is quite easily explained. This is but an indication of the dynamic changes to which this and other rocks have been subjected. But, as we are studying the feldspar under the glass, we notice, here and there, inclosed in the feldspar little amber colored crystals. They are in the shape of four-sided prisms, and shine with an adamantine lustre. They are crystals of the mineral zircon. Though they are in this rock they are not an essential part of it; they are simply, as it were, accidental. This rock contains the minerals of granite. The feldspar is abundant and the quartz not more so than might be expected in granite; yet the rock has a marked foliated, almost banded structure, resulting from the arrangement of the minerals. The latter are characteristics of gneiss. Because of the resemblance which this rock bears to both granite and gneiss it may be called a gneissoid granite.

Hornblendic mica schist or gneiss.

(2) Lying adjacent to, and just east of, this first band is a very different rock. This is five feet in width. It consists of alternating light and dark bands varying in thickness from one-eighth to one-half inch. The dark bands are characterized by an abundance of dark brownish mica. The fine scales of the mica are so abundant as to conceal quite effectually the feldspar and quartz, which are

also present in fine particles, and cannot be distinguished even under the magnifying glass. The lighter bands have a greenish color because of the small particles of light green hornblende distributed quite abundantly through them. There may be seen in these also a dark, greenish black hornblende occurring in small, blade-like masses, sometimes a half inch in length. On closer examination of the greenish bands under the magnifying glass there are seen, scattered here and there, little amber colored crystals. We cannot make out their crystalline form, but think they are most likely little amber colored garnets. These are not, however, an essential part of the rock, and attract our attention by their color before other minerals, which are more important in helping us to name the rock. There are also quartz of a bluish, smoky tint, and feldspar, both in fine particles.

These alternating light and dark bands are generally perfectly distinct so that a pencil may be drawn along the dividing line. The rock of this second band of the quarry, because of its banded structure and the minerals it contains, may be called a gneiss, though the more micaceous, small bands may, by themselves, be called mica schist, and the hornblendic bands, hornblende gneiss.

Gneissoid granite.

(3) Next east of this banded gneiss is another band twenty-four feet wide, of coarse, light colored gneissoid granite like the first band.

Biotite schist resembling a metamorphic conglomerate.

(4) Then east of this is found a band, also twenty-four feet in width. It consists largely of a dark grey biotite or black mica arranged so as to give a laminated structure. This may properly be called biotite schist. Imbedded in it are thin, wide, long masses of lighter rock which on cross-sections appear as long, wavy, narrow bands or streamers. This lighter rock substance is mainly white, coarse, pearly feldspar with fine granular quartz, and is frequently divided into rounded or lens-shaped masses by films of biotite, producing a resemblance to flattened pebbles in a metamorphic conglomerate.

Also resembles a metamorphic conglomerate.

(5) Next is a band, twenty-one feet wide, of rock resembling the last, but coarser in texture, in which the pebbly character is even more clearly brought out.

Hornblendic biotite gneiss or schist.

(6) Then there is a band, thirty-five feet wide, made up of narrower alternating bands of biotite and hornblende gneiss, brought out clearly by the

A Slab Showing the Alternating Laminae of Hornblende and Mica Schists, Quinsigamond Quarry.

variation in color; and now and then there is a band much lighter in color than the average of either.

Light grey granite.

(7) Continuing our study to the east, we next meet a rock quite different in appearance from any before met. It is of a light grey or slightly brownish grey color; and consists of a fine grained mixture of quartz, feldspar and mica. These minerals are arranged so as to give a distinct finely banded structure parallel to the strike of the rock of the quarry. These fine bands are about one sixteenth of an inch thick, and are grouped together so as to give a coarser banding; in addition there are other bands six to twelve inches thick, uniform in color and not showing any bands within themselves, but having a distinct foliation due to the arrangement of the minerals. There is no clearly defined line between the light grey which shows the banding of a gneiss to perfection and the fine brownish grey which is without banding, and has only the foliation. They blend into each other, but the light grey banded is on the border next to the neighboring rock of the quarry floor.

As we study this rock in the fragments lying about, our attention will, very likely, be attracted by some pieces which show what at first appears to be a banding directly across the foliation of the rock. There are alternating bands of brownish grey, the normal color of the rock, and of light green. On examining these greenish bands carefully, we see, extending through each and following the middle plane, a vein of quartz; from this vein the green extends and blends into the brownish grey. From this observation we are able to explain this peculiar banding. Where the vein now is, was first a crack; through this crack water, containing mineral substances in solution, slowly percolated and soaked into the rock on either side of the crack, carrying in mineral matter or withdrawing mineral matter from the minerals of the rock thus changing the brownish mica and producing a mineral of a light green color. What the latter is cannot be made out exactly on account of its fineness. It is probably a chlorite. From this we see how percolating waters may produce a regular and distinct banding within a massive rock. It is clear from this that banding does not always indicate a former sedimentary state. This banding is not, however, to be confused with the finer and more regular banding in this same rock described above. Taken as a whole this rock has the appearance of a gneiss. It is composed of quartz,

feldspar and mica, and has more or less of a banded structure. especially on its borders; nevertheless from other considerations we have concluded that it is really another kind of rock, as will appear in our discussion of the band marked (12).

Gneissoid granite.

(8) Then follows a narrow band, three feet wide, of coarse gneissoid granite similar to that already described.

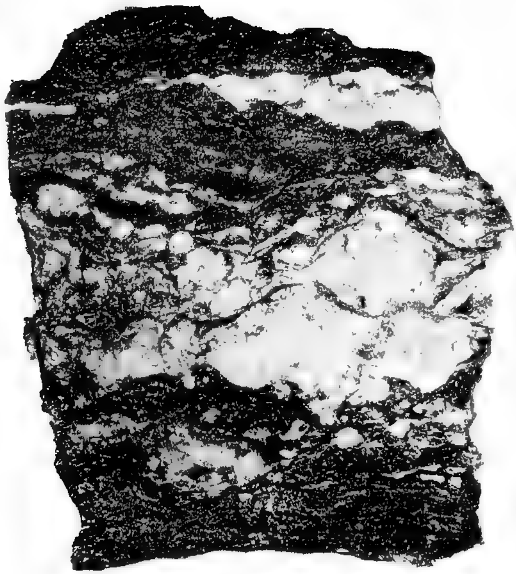
(9) Next there are sixteen feet of a mixture of light and dark gneiss or schist in bands one to two feet wide. The dark bands are of a biotite or black mica gneiss or schist; the light bands are partly coarse and partly fine, with dark streaks of biotite running through them, parallel to the general banding of the quarry rock. In the coarser part the feldspar masses are coated with light yellowish mica scales, and the outside rim is frequently a finely granular zone. These two facts tell us of a crushing and crunching of these feldspars by which mica was formed out of the feldspar on the friction surfaces, and the feldspars were granulated more or less from the surface towards their centres. Little facts like these will frequently reveal to us the dynamic changes to which rocks have been subjected.

Schist containing pebble-like inclusion.

(10) Continuing our observations across the quarry, we next find a band, twenty-five feet wide, of dark grey biotite gneiss or schist containing lighter colored, narrow bands, a few inches in width. These latter show a marked pebble-like structure, like that already described. These lighter bands are also frequently crumpled into many fine folds. These will tell us somewhat of the condition of this rock when this folding took place. For, certainly, these bands could not now be so folded without breaking.

Gneissoid granite.

(11) We next come to a band of gneissoid granite about seven feet in width. This band is less regular than the others, while the rock is practically the same as in the other gneissoid granite bands. This constitutes an irregular lens-shaped mass. Into it extend the laminae of the neighboring biotite schist in delicate streamers. This gneissoid granite is coarsely crystalline, the feldspars being from one to two inches through, and the foliation is traced with difficulty. This is decidedly granitic in structure, appearance and position, yet possesses the same characteristics found in the gneissoid granite in the numerous bands already described.



Pseudo-metamorphic Conglomerate. Granite Injected into Mica Schist. From Ballard's Quarry, Near Quinsigamond. Natural Size.

A Slab from Quinsigamond Quarry, Showing Ragged Ends of the Schist Laminae on Either Side, and Injected Coarse Granite, with Dike of Fine Brownish-grey Granite Cutting Across Both.

Fine grained, brownish grey granite.

(12) Then we find a brownish grey, finely grained, biotite rock, more or less clearly foliated, and evidently the same as that described under (7). This band is but three to four feet wide, and at first may seem unimportant; but really it presents facts which help us greatly. We see laminae of the dark banded adjacent gneiss extending into this finer grained rock and growing thinner and thinner until they end in sharp, ragged edges. These are like streamers protruding into this neighboring rock so gneissoid in appearance.

In fact in one slab, shown in the illustration, were found the opposite ragged ends of the schist where the schist had been torn asunder, and this fine grained rock had filled the break and gone into the small, ragged irregularities without disturbing them or breaking the sharp edges. Certainly this fine grained rock must have been in an exceedingly plastic and mobile condition to thus fill in and include, without breaking, these delicate streamers of the schist. Moreover we here find this fine grained gneissoid rock in contact with the coarse gneissoid granite. Instead of constituting a band, lying alongside of the granite gneiss, this fine grained rock cuts across the coarser, as if the latter had been broken, and the finer had flowed in and filled the break. In other words, gneissoid though this finely grained, brownish grey rock may be in appearance, its occurrence forces us to believe that it was in a molten or plastic state when it came into its present position. It is, then, a granite and not a gneiss.

But if this is a granite, we may properly inquire why it is that it shows such perfect banding, as is described under (7), especially next to its contact with the neighboring rock. As was pointed out, this banding fades out as the distance from the contact increases, until there is simply an indistinct foliation. The border banding is the result of selective crystallization during the cooling and solidification of this rock. It came into its present position while in a molten condition, filling fissures or cracks in the neighboring rock. The latter was comparatively cool, though probably still heated much above its present temperature. The molten rock flowing into the fissures, was cooled, minerals began to crystallize from the molten rock, not all together, but more of this one first, then more of that one. Such a crystallization, where minerals vary in color, must produce a regular variation in color, and hence a banding. But while we may see that the banding is due to this

selective crystallization, it is not so easy to see why a like crystallization did not continue through the mass. There is hardly more than a trace of it in the midst of this fine grained granite. We conclude then that the cooler neighboring rocks together with the motion in the molten mass as it flowed into the fissures, produced conditions specially favorable for this selective crystallization, conditions which did not prevail, or prevailed to a much smaller degree, during the crystallization of the great mass of this granite away from the surfaces of the neighboring rock.

Gneissoid granite.

(13) There is next a band of coarse, white gneissoid granite, nine feet wide, and penetrated by the grey granite just described.

Biotite schist and gneissoid granite.

(14) Then three feet of the dark biotite schist followed by twelve feet of narrow, alternating bands of light gneissoid granite and dark biotite schist, the granite bands fading out in each direction.

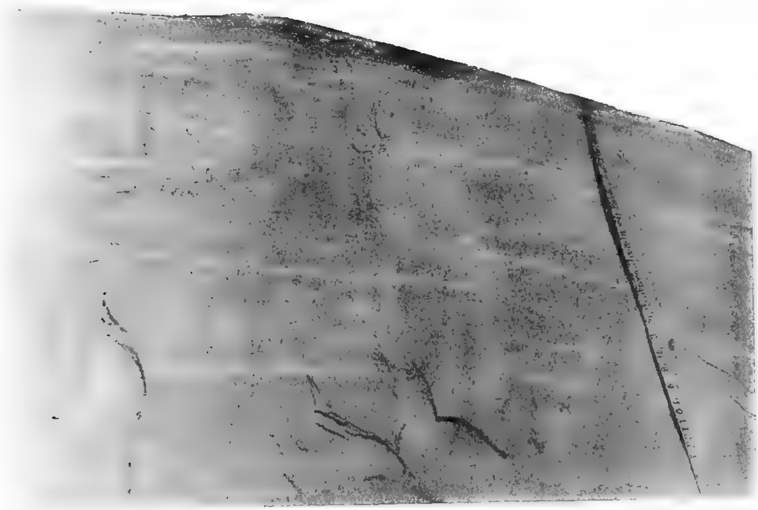
Gneissoid granite.

(15) Last at the eastern side of the quarry is a band, twenty-six feet wide, consisting almost entirely of the gneissoid granite with, now and then, a narrow band of the biotite schist, this gneissoid granite being essentially the same as the gneissoid granite of the other bands.

We have thus described, band by band, what is found in the floor of this quarry in crossing from west to east midway between the northern and southern ends. These bands make up together a width of about two hundred and fifty feet. This description has been given in such detail to bring out clearly the exceeding complexity here presented, and to give a clear idea of the various rocks here found.

Grouping of the bands. Time relation of the rocks.

In spite of the many apparently disconnected, parallel bands, it is quite evident from the descriptions that all of these rocks may be classed as four; the light colored, coarsely foliated gneissoid granite, the fine grey granite, and the biotite hornblende schist or gneiss, and the coarse, dark grey biotite schist with pebble-like inclosures. From the descriptions that have been given, it is evident that these four rocks bear a certain time-relation to each other. The gneissoid granite includes streamers of the schist and fills into little irregularities where the laminae of the schist were evidently broken or torn off; then, evidently, the schist must have been there first, and the coarse granite must have been in an



A Slab of the Fine, Brownish-grey Granite, Showing Perfect, Fine Banding Near the Upper Edge, and the Fading out of the Banding as the Distance from the Contact Increases.

exceedingly plastic state to have thus inclosed, without breaking, or destroying, these fine, delicate streamers of the schist. We must consequently consider the coarse gneissoid granite, in spite of its marked foliation and gneissoid appearance, a true granite. It is in its present position, younger than the schist.

But we have already pointed out that the finely grained, brownish grey granite not only includes streamers of the schist, but also cuts across the coarse gneissoid granite, evidently filling a break in the latter. The brownish grey granite is, therefore, younger than either of the other two,—is the youngest rock met in the floor of this quarry.

Such being the rocks seen at this locality and the time relation they bear to each other, we may turn to the oldest one, and inquire what may have been the history of these bands of mica schist. For the sake of simplicity, it will be well for us to divide the mica schist here found into three kinds, though they are all closely related, and consider each by itself.

Origin of the mica hornblende schist.

There is first the mica schist consisting of alternating bands some of which are brownish, and some are light, greenish grey in color. Although the material of this schist is thoroughly recrystallized, its banded structure and composition indicate that it has not always been as it now is. Its composition indicates a sorting of rock materials, just as such substances are sorted by currents of water; and the banded structure, though now appearing in crystalline material, also points back to rock material arranged in layers or strata, just as the sands deposited by water are so arranged. Moreover, the material deposited by water in one layer may not be entirely of one mineral because of imperfect sorting. One layer may be sandy and at the same time argillaceous, because the waters deposited sand and clay together; another layer may be ferruginous because iron rust was deposited with the sediments; in like manner another may be calcareous. If layers of such mixed sediments undergo a recrystallization and a chemical rearrangement, as the result of the action on them of heated waters under pressure, one layer may differ from another in its minerals, and hence in color and appearance, but still the rock, as a whole, preserve the original bedding.

This in brief is the history of the mica hornblende schist. It was once sediment deposited in layers of varying composition in

the shallow waters of some ancient sea; these sediments were covered by other rock strata, also deposited in that ancient sea, so that these sediments came to be quite deep within the earth; there they were recrystallized through the agency of hot waters under pressure; afterwards they were brought to the surface, where now they appear, by the removal of the overlying rocks.

A mica schist which is a pseudo-metamorphic conglomerate.

The second variety in the schist bands is in part a schist closely resembling the mica schist of the brownish bands of the hornblende mica schist. The mica is a dark brown biotite, somewhat coarser than that in the first schist, and is mixed with some glassy quartz and probably also with feldspar. The other part of this schist, and that which distinguishes it from the other schist, is a crystalline mixture of quartz and feldspar with some coarse biotite mica. This granite-like material is sometimes distributed in quite well defined bands, sometimes narrow, sometimes wide, parallel to the laminae of the schist. These bands are nearly white, and may be seen to be made up of rounded feldspars with coarse, glassy, granular quartz between, or made up of rounded individuals of a mixture of the same pearly white feldspar and glassy quartz with black biotite wrapping partially around these individuals and more or less clearly separating them. In other cases these bands are less regular and become narrower, and more or less discontinuous. The rounded feldspar, or feldspar-quartz individuals, then become more and more distinct and separated, until they may be found, as single individuals so far as can be seen on a cross-section, inclosed in and entirely surrounded by the schist. Such individuals are generally rounded feldspars, less frequently rounded masses of feldspar and glassy quartz, and, least frequently, rounded individuals of massive, glassy quartz. These individuals vary in size from half an inch or less up to two or three inches on their largest diameter, and they are uniformly flattened in a direction parallel to the lamination of the schist. The appearance, which we have tried to describe, closely resembles what might possibly be produced by the recrystallization or metamorphism of a conglomerate, the schist bands and mica being made from the fine, sandy feldspathic material separating layers of pebbles, and also inclosing individual pebbles, and the rounded feldspar, feldspar-quartz, and quartz individuals being the pebbles flattened by great pressure. It is a subject for study to determine whether or no this part of the quarry rock is a metamorphic conglomerate.

In the first place it has been shown that there is much granite in this quarry rock that has been parallelly injected between the laminae. Some of the continuous bands in this schist are not to be distinguished from these true granite bands; the former grade into those which have the pebble-like structure, or the same band may be partly true granite and partly pebbly in structure. Moreover the material of the individual, rounded, pebble-like masses is identical with that of the coarse granite, except in the case of the massive, glassy quartz particles; and this resembles matter that has crystallized from solution or aqueous fusion in place, rather than material that has been worked over by the agents of air and water before being buried in the rock. After careful comparison and study, we have been led to believe that all of these light-colored bands are composed of granite, and that the pebbly structure is due to a slow crystallization of the material under a normal pressure. Even the particles which are entirely separated from other granite have had a like origin. This schist is not really different from the brown mica schist with the hornblende schist; it is the brown schist into the midst of which granite, in somewhat thinner sheets, has been injected, producing a little coarser crystallization and a pebble-like appearance.

Chloritic biotite schist also pseudo-conglomeratic.

The third type of schist found in this quarry is a pure biotite schist of a dark grey, almost black color. The biotite is sometimes coarse and sometimes fine, and produces a thinly laminated structure. The surfaces of these laminae are frequently greenish in color indicating the presence of chlorite, so that this schist may sometimes be called a chlorite biotite schist. Between the laminae of this schist, also, has been injected granite, sometimes now appearing in regular bands, sometimes in discontinuous sheets and separate, distinct lens-shaped masses an inch or two in diameter. This injected granite also presents the pebble-like structure. This schist, like the others, is but a recrystallized sediment. It was made from layers that were more nearly pure clay, and contained much less sand, hence it contains little or no glassy granular quartz.

Position of the laminae and bands evidence of folding.

But while these changes were taking place in the mineral constituents of this rock, another important change took place. In going across the quarry we noted that every thing is in bands. These bands are the edges of the laminae or layers of the original

rock, and of the intruded granite sheets. These layers are now nearly vertical. When deposited, the layers of the sediments must have been horizontal, or nearly so. There has been a change by which these layers have been uplifted from a horizontal to a nearly upright position. The meaning of this is that these beds have been folded. To make this clear in our minds let us think of strips of paper, four feet in length and six inches or so in width, and of different colors; then let the red ones first be laid down, one on top of another, until they make a layer one half inch in thickness; then let the yellow strips be laid down on top of the red to a like thickness, and then on these blue strips, and on these still others, until the sheets of paper constitute a long, narrow pile a few inches in thickness. That the paper may be more pliable, let it be moistened; then think of the ends of this mass of paper as pushed towards each other; the paper mass, as it is compressed, bends into several folds; and if the ends are pushed towards each other with considerable force, the sides of these folds will be pressed together and may stand vertically, or nearly so. If now with a sharp knife we cut through, horizontally, midway between the top and the bottom of these folds, and remove that part of the fold above the cut, there will be presented to us, as we look down on the folded paper, a banded appearance where each band is really the edge of a layer of colored paper, and these layers are now vertical, or nearly so, because of the folding that has taken place. That is exactly the meaning of the nearly vertical layers or laminae in the schist in the floor of this quarry. They are situated in the sides of more or less extensive folds, the upper parts of which have been removed by the great erosion to which this area has been subjected during long geologic periods.

Small folds in a plane at right angles to that of the large folds.

In going longitudinally through the quarry we frequently observe that these bands are wavy in form. In places these waves are so abundant that the bands present the appearance of having been crumpled into many folds, many of them even minute. These folds are not to be confused with those larger and grander ones which, if built up as they formerly were, would extend hundreds, perhaps thousands, of feet into the air. These smaller folds are not in the same plane with the larger ones; and while the larger folds indicate a compression easterly and westerly, these smaller folds indicate a compression northerly and

A Block of Rock at the Ballard Quarry; the Wavy, Fine Bands are Schist; the Coarse, Light Band in the Middle is the Coarse Gneissoid Granite.

southerly. Moreover these small folds are on such a scale that we may see a succession of them. So nicely was this minute folding done that this hard, brittle rock material was bent into innumerable, closely folded waves without a crack or fissure appearing throughout the mass. This minute folding may be seen to better advantage on the ledges in the woods north of Gibbs street and just east of the gulch at the foot of which is a stone bridge over which the street extends. Such folding shows us very clearly much in regard to the condition of the rock when this folding took place. What is now brittle, unyielding material must then have been exceedingly pliable and flexible. When this folding took place, these rocks were deep within the earth and under enormous pressure; they were also quite highly heated so that their moisture was converted into steam, which could not escape on account of the pressure. Under these conditions the hard, brittle, solid rock substance became as yielding as clay on the potter's wheel—pliable, flexible, bending into folds innumerable without the mixing or mingling of band with band. Sometimes this folding took place as the result of the intrusion of the granite, for the schist laminae were forced out of position and folded around the granite mass. More frequently granite sheets and schist laminae were crumpled together into a series of beautiful and minute folds. The latter folding must have taken place after the granite was in place; and the granite offered no more resistance than did the schist.

Condition of the rock at the time of folding.

Difficulty in estimating thickness of the schists.

It is an interesting problem, geologically, to determine, if possible, the thickness of the schists, and from this the thickness of the original sedimentaries out of which these schists were formed. Within the quarry this is easily done by simply measuring band after band, for everything is there uncovered. Such direct measurement is not possible when we deal with the formation as a whole, because by far the larger part of the formation is covered by sands, gravels and till. Neither is the proportion of granite the same throughout the formation as it is in the quarry. In fact it is impossible to determine with any degree of accuracy how much of this mixed formation is either schist or granite.

Then add to this difficulty that which comes from the crumpling and folding in this formation by which the same laminae may be

repeated again and again without our being able to identify them as the same, and it is seen that the problem of determining the real thickness of these schists is well nigh insoluble.

Possible cause of the folding of the schists.

This quarry and the Bolton gneiss formation are an excellent illustration of an idea that Prof. Van Hise has recently expressed. The granite constituting more than half of the rock of the quarry and a large part of the whole formation, came, as we have said, from a greater depth within the earth up into these sedimentaries, and there solidified and remained. By this transference the rock material beneath was decreased, and that nearer the surface was increased. The outer part of the earth became, by just so much, larger, and the interior became, by just so much, smaller. The sedimentaries occupied a certain space in the earth; to have forced into their midst this large proportion of granite must have necessitated a giving and yielding in some direction. This yielding very likely took the form of folding and elevation of the beds of which there is so much evidence.

Connection between the sheets of granite.

We have already seen, in the case of Millstone Hill, how a mass of molten rock may rise from beneath through some fissure, and constitute a single, large intrusive mass in the midst of sedimentaries, and cool and crystallize into what has been called a batholite. But this is quite different from what is presented at this Quinsigamond quarry. Yet the two occurrences of granite are not, probably, as unlike as they at first seem. We can hardly believe that these many sheets of coarse granite, so alike, are entirely disconnected. Yet we may follow a schist band for quite a distance, and find it separating two granite sheets as far as we go, or as far as the rock surface is uncovered. These two neighboring granite sheets have no visible connection. But if we could trace these bands down into the earth, we should, in all probability, find the schist bands growing thinner and the granite sheets thicker, until the former ceased to separate the latter,—until the whole rock became granite. There we should find an extensive mass of granite, constituting a large batholite, and corresponding to the single granite mass of Millstone Hill. These granite sheets, whose edges we see, are but offshoots from this larger mass, passing up between the laminae of the schist. At some future time, as the rocks now at the surface in this region are removed, lowering the surface

more and more, this large mass of buried granite may become exposed.

Brief review of the history of these rocks.

Having traced back, step by step, the relation of the rocks in this quarry, it will be well for us, in review, to state the facts in reverse order somewhat as they occurred.

In an ancient geologic period the material of these schists was deposited as sediments along the shores of the continent of that time. What we now see is but a small part of those ancient sediments, because of the great erosion to which they have been subjected. These sediments were covered by others so that the former were deep within the earth. Then followed a period of disturbance and change. The strata, originally horizontal, were folded and crumpled into both large and small folds; and, accompanying the folding, perhaps as a cause, perhaps as a result, there rose from some greater depth a large mass of molten rock, from which offshoots flowed in between the laminae of the schist. By the folding of the strata and the intrusion of this molten granite, the sediments were highly heated and partially dissolved in the hot waters; then as the heated rock mixture cooled, the partially dissolved sediments became the crystalline schist and the intrusive molten rock became the coarse, light grey granite. After these rocks had cooled considerably, but while the schist was still flexible and yielding, again, through a deep fissure in the rock beneath, molten rock rose into the midst of this alternation of schist and granite. It found a way generally through openings between the laminae of the schist, or between schist and granite, but in places flowed into breaks across both laminae of the schist and sheets of the granite. This later intrusive cooled more rapidly than did the older granite, as is indicated by its fine, granular texture. This second intrusive is the fine, brownish grey granite.

Quarry a mineral locality.

But the rocks in this quarry are not the only objects of interest. On a small scale this is quite a mineral locality, and what the minerals may lack in quality they make up in number of species. In addition to the constituent minerals of the rock, the quartz, the mica and the feldspar, we have pointed out that in the coarse granite may be found little

Zircon.

zircon crystals of a brownish color, having the form of a four-sided prism. These little crystals are not limited to the coarse granite in any special part of the quarry, but

may be found in any part of that rock, if only one looks sharply enough, and uses a fairly good hand magnifying glass. We must class this zircon as an original mineral in this rock; and it evidently crystallized before the mineral matter around it solidified, because it assumed so perfect a crystalline form, and is inclosed by the other minerals.

Allanite.

In studying the coarse granite in the southern part of the quarry, our attention may be attracted by a peculiar appearance that this rock sometimes presents. We may see on its surface, here and there, a little black spot, frequently not more than one sixteenth of an inch in diameter. The rock around this black spot may be rusty in appearance, which may be due to gummite which forms from the alteration of allanite; but more peculiar and remarkable is the manner in which the rock substance is puckered around the black spot. This appearance in the inclosing rock will serve to distinguish the black mineral constituting this black spot from black mica. After examining several of these black spots, we see that the mineral is a black mineral having a coal-like lustre, and is in the form of prisms which do not show clearly the crystalline form of this mineral, but belong to the monoclinic system. The prisms here vary in length from the merest fraction of an inch to half an inch, and in width or thickness from one sixteenth up to one half inch. The quite large crystals are extremely rare. This mineral is allanite, and is evidently also an original mineral, inclosed as it is in the very midst of this granite. When these crystals formed and the inclosing rock solidified, for some reason the rock puckered around the mineral as if the former had been drawn up by a string.

Hornblende and amber colored garnets.

But the schist bands, as well as the granite, are interesting on account of the contained minerals. It has already been pointed out that some of these bands contain both light green and dark green hornblende. In places this hornblende is coarse enough to give us a clear idea of the appearance of this mineral, including its lustre and cleavage. In these hornblende bands are, as we have already pointed out, little, dark amber colored garnets which are too small to be seen by the unaided eye. Even under the magnifying glass their crystalline shape does not appear. They were evidently formed when the ancient sediments were recrystallized into the schists.

Garnetiferous mica schist.

The mica schist bands are also of interest in this connection and will reward us for careful searching. Not everywhere in these bands may we find this next mineral. Only now and then does it appear imbedded in the coarse, dark mica schist. This is a beautiful wine colored garnet, clear as crystal, and occurs quite abundantly in some bands, and in good sized crystals. We long to get them out of the rock, but all in vain, for they are securely held by the inclosing laminae of the schist. If we try to break them out, we are disappointed in seeing them fly to pieces. Nor are we able to make out any exact crystalline form; they seem to be slightly flattened in the direction parallel to the laminae of the schist, thus indicating the pressure to which this rock has been subjected. They were formed in the laminae of the schist when the other constituents were crystallized, and are original minerals.

Graphite in mica schist.

But this somewhat coarse garnetiferous schist has more to repay us for our study. While examining it carefully under the magnifying glass, our attention is attracted to little scaly particles of a bright metallic lustre and of a dark grey color. These particles prove to be very soft, and leave a mark on paper, when detached from the rock and drawn across the white surface. These are evidently little scales of graphite. They, like the garnets, must have been crystallized in the schist along with the other minerals. As graphite is a form of carbon, we may justly ask how it happens to be here in this schist. Carbon, as we all know, is the foundation of plant and animal substances. By heat the carbon contained in these is, to a greater or less degree, set free, as when wood is converted into charcoal. If, then, in these ancient sediments, which now appear in the form of this schist, there were buried leaves and twigs and other vegetable or animal matter, upon being heated, as they must have been when the rock was recrystallized, these substances must have been converted into free carbon, and with sufficient heat this carbon must have crystallized into the form of graphite. We shall not think wrongly, then, if these little scales of graphite stand for the ancient plants that lived while the material of this rock was being deposited in an ancient geologic time.

Black hornblende in the mica schist.

In this same dark, coarse mica schist we notice, here and there, little black, shining needles. At first they make us think of tourmaline prisms, but they do not show the ribbed surface characteristic of

tourmaline and show a distinct cleavage, and so we recognize them as needles of black hornblende. It, too, is an original mineral and was crystallized with the rock.

Garnetiferous gneiss.

Another specimen from this quarry is worthy of description, not because of any new mineral in it, but because of the pleasing effect of the combination of minerals within it. The rock contains so little mica and so much quartz and feldspar, that it may be called a gneiss instead of a schist. It is thinly laminated, and contains biotite with fine muscovite. The quartz and feldspar are finely granular, and so intimately mix as to be indistinguishable. This granular mixture constitutes wavy bands separated by mica. Through the granular mixture are distributed many wine colored garnets, clear as crystal, giving a slight rosy tint to the whole surface of this rock. On only one occasion have we found this phase of the schist at this quarry, and then not in large quantity.

Original and secondary minerals.

The minerals thus far described are those which must have been formed when the rocks crystallized, and are therefore called original. There are other minerals found in the quarry in quite different occurrences, indicating that they have been formed at later times. These may be called secondary minerals.

Calcite.

The first and most abundant of these latter minerals is calcite. It is found coating quite large surfaces, which border cracks extending through the ledge. This mineral is found especially on the walls of the eastern side of the quarry. It is generally of a pure white color, so soft as to be easily scratched by the knife blade, and effervesces freely when touched by a drop of hydrochloric acid. It also shows a perfect cleavage, breaking into little rhombohedra. It results from the decay of the granite and schist. Water from the air, containing carbonic acid, soaks into the rock. The carbonic acid is thus brought in contact with feldspar and other minerals containing calcium, and unites with the calcium, forming carbonate of calcium, which is calcite. The calcite is then carried, in solution in the water, into the cracks, and there is deposited on the surface as a coating, at times even filling the crack.

Quartz crystals.

Occurring in like manner, but brought in and deposited by hot water containing potash, are little quartz crystals. Some of these are colorless and

transparent, clear as the clearest glass, and, though small, showing to perfection the six-sided prism with the six-sided pyramid. Other of the quartz crystals are dull in lustre, either milky white or slightly rusty in color, and only slightly translucent. These variations are probably due to a variation in the conditions which prevailed during the formation of the different crystals.

Chabazite. While looking for the calcite or the quartz crystals, we may notice a mineral occurring with both the calcite and quartz. It is of a light amber color, and is in nicely defined crystals. These crystals, at first sight, seem to be cubical in shape; but on more careful examination are seen to have angles not exactly right angles. These little amber colored rhombohedra are the crystals of the mineral chabazite. Occurring in the fissures, it is, evidently, a secondary mineral, and has been formed from other minerals of the rock, and crystallized from the percolating waters. Nice crystals of this mineral may be justly prized as coming from this locality. They constitute beautiful little specimens.

Stilbite. Closely related to the last is another mineral also found in the fissures in the eastern part of the quarry. It belongs to the same family of minerals, and, like the chabazite, is the result of the chemical decomposition of certain minerals in the granite or schist. It is not, however, so frequently found, and its crystals are not so noticeable, and hence do not so quickly attract the attention. This mineral is almost pure white in color, and in fine, thin, flat blade-like crystals, pointing in almost every direction and crossing each other at various angles, forming a mat or network. These crystals are also marked by a pearly lustre from which it received its name. It is the mineral stilbite. It has thus far been found only as a thin coating on fissure surfaces.

Prehnite. But if we examine carefully the crevices and fissures in the eastern part of the quarry, we may find one which has been entirely filled with mineral matter. This mineral filling may be clearly distinguished from the inclosing rock. This mineral constitutes a vein. It is glassy in lustre, and white or light green in color. It is so hard that the knife blade barely scratches it. We see, from the shining surfaces that are presented as the specimen is moved in the light, that the vein is made up of fine crystals. After breaking out some of one of these veins, we may be fortunate enough to find a place where the mineral

did not completely fill the fissure, and there the distinct crystals appear. When free from iron rust, they are white or of a light green color. The little crystals are little plates, tabular in shape, standing on their edges at various angles and without uniformity in direction. They make a confused mass in which, however, we are able to distinguish the shape of the individual plates under the magnifying glass. We see clearly three and four sides on the edges of these little plates, and can fill in the remaining sides from the regularity of form, thus making out that these plates have six sides, each, around the edge. This mineral is known as prehnite. It has been formed by chemical decomposition in the neighboring granite, and has been deposited in these cracks and fissures through the agency of water.

Pyrrhotite.

After visiting this quarry, more or less frequently, during eighteen years one might reasonably think that all the minerals occurring here had been observed; nevertheless on visiting this quarry on the 14th of April, 1900, another, not before observed here, was found in considerable quantity. The rock in the vicinity of it was marked by extreme rustiness and by a honey-comb appearance. This is due to the fact that the mineral rusts rapidly, thus coating the neighboring rocks, and is quickly removed from the rock, leaving the spaces it filled as cavities. These changes require oxygen from the air, and so do not take place until the mineral is within reach of the air. On examining this mineral it is seen to occur in a quartz vein within a schist band. The mineral is of a bronzy color; has, when free from rust, a bright metallic lustre; is quite heavy, having a specific gravity of 4.6; and is slightly attracted by the magnet. These properties indicate clearly that the mineral is pyrrhotite or magnetic pyrites. As this mineral frequently contains nickel, and is, in fact, the principal ore of nickel, the question immediately arose whether or not this particular pyrrhotite contains nickel. In it may be found nickel enough to give a decided test. As this mineral occurs inclosed in the glassy quartz of a quartz vein, it must be as old in its position as is the quartz and must have got into its position much as the quartz did. The quartz vein, like other veins, is the filling of a crack or fissure; the quartz of it was brought in and there deposited through the agency of water. In like manner must this mineral have been deposited along with the quartz.

Epidote. On visiting this quarry we must not expect that these minerals will be so obvious that we cannot overlook them; we must have our sharp eyes on, use these to the best advantage, go slowly in our search, and examine everything through the hand magnifying glass. Working in this way, and being constantly on the lookout for any fact, we notice that, now and then, the surface or edge of a slab, which has been broken out of the quarry, has a greenish yellow color. The first thought is that a fine moss is growing on this surface; but through the magnifying glass a single glance is sufficient to remove this idea. The surface is seen to be covered by a thin coating of glassy crystals, shining and flashing in the sunlight. Some of the crystals are large enough to be seen as transparent, greenish yellow prisms. There is no mistaking this mineral, it is epidote. It is also a secondary mineral formed from other minerals, and deposited as a coating on these surfaces. We may in other localities find larger crystals of epidote, but we shall not find any that are prettier.

Vermiculite. Another mineral we may find in the eastern part of the quarry, also coating surfaces, is almost black in color on the outside, but within is dark green. It occurs in small tufted masses, crowded together over the surface. On examination under the glass we see that each tuft is a mass of little black or dark green plates pressed together. Where one of these tufts happens to be broken, it is seen to be a mass of scales resembling mica scales, and we may think that possibly this is only a variety of mica. On heating a few of these tufts in the blowpipe flame, this mineral begins to squirm and twist and turn inside out, as if it were truly animated and were suffering excruciating pain. Not so, however; this strange effect is but the passing off of water that was held confined in the substance. Because of this twisting and squirming when heated, the mineral was called vermiculite, a wormlike stone. The neighboring town of Millbury has long been noted among mineralogists as affording this mineral.

Prochlorite. Quite closely related to the last mineral, and like it occurring as a thin coating, is still another mineral. It, too, is of a dark green color, and so soft as to be easily cut by the finger nail, when the green color more clearly appears. It is, at its best, a mat of fine, dark green scales, and is readily recognized as prochlorite. This mineral is frequently found as a secondary mineral in connection with hornblende rocks, and it is possible

that here it has been derived from the hornblende in the schist.

Iron pyrites, copper pyrites, malachite, azurite, actinolite.

There are other minerals that have been found here, but only in small quantity. There is iron pyrites, almost omnipresent in the rocks of Worcester, easily recognized by its light brassy color and its hardness. Then there is chalcopyrite, or copper pyrites, occurring more abundantly on the surfaces of joints and seams, and distinguished from iron pyrites by its darker yellow, brassy color and by its softness, being easily scratched by the knife blade. Associated with the last mineral may be seen, at times, in small quantity, the green and blue carbonates of copper, malachite and azurite. The copper in them was derived from the copper pyrites, and carbonic acid was carried in by the percolating water. Last of all there is a beautiful form of actinolite that has been found here. Some years ago the quarrymen opened up quite a large vein of smoky quartz which contained radiating masses, an inch or a little more in diameter, of a light green mineral. These masses consisted of fine, silky fibres radiating from a centre, and the mineral was as beautiful and delicate as the finest silk. These radiating masses were exposed as the workmen broke into this vein. The mineral was recognized as a very fine actinolite. Either because work was given up in that part of the quarry or because the supply was exhausted, that form of actinolite has not since been found. There is another form of actinolite consisting of long, black needles, more or less radiating, which is still found in different parts of the quarry.

This quarry a hand specimen of a large area.

In this somewhat extended study of the rocks and minerals at the Quinsigamond quarry it must be borne in mind that it has not been a study simply of that small detached area, though that would abundantly repay us, but a study of a large area extending many miles to the south, and several miles to the east beyond the bounds of Worcester. We have been studying a somewhat large hand specimen of the Bolton gneiss instead of the whole broad area. In doing this we have not observed some facts and minerals appearing in other parts of this formation which do not appear here. To complete our study we must notice these.

Fibrolite mica schist.

Going out on the Boston and Albany railroad to the east from the deep cut at Bloomingdale, we come to a wooden bridge, painted red, spanning the tracks.

This bridge rests on ledge at either end. The rock of this ledge is a compact, massive mica schist, and a part of the great schist and granite area which is the subject of our study. On breaking into the ledge here, in certain bands, we find the schist containing quite long, glassy needles, colorless or rusty, at times so abundant and crossing each other in so many directions as to make a perfect network. The needles are but a small fraction of an inch in thickness, but in length may be a full inch or more. On examining these needles through the magnifying glass they are seen to consist of exceedingly fine, glassy, colorless fibres extending from end to end of the needles. A nice specimen of this rock with the contained mineral will add to any mineral collection, for it shows a phase of this mineral not frequently met in this vicinity. This mineral has been called, on account of its structure, fibrolite. It also bears the name Sillimanite, in honor of Benjamin Silliman, the first professor of geology at Yale.

Millbury limestone.

There is another locality of considerable interest within the Bolton gneiss. Leaving the electric car at Bramanville, we go to that part of Millbury called Old Common, thence follow the road to the south. Immediately, at the first small rise, we notice the rusty color of the dirt in the road; and then, at the top of this rise, we see in the road and by the side a rock of peculiar appearance compared with those before met in this study. Moreover, in the bank on the right we may see more of this rock, here marked by its extremely rusty appearance, and by the ease and rapidity with which it evidently decays. Still farther on, also on the right, there is an opening made into the bank where the rock is better exposed, and more easy of access. There are also many fragments which have been thrown out, and these may help us greatly in our study.

As before, we notice the extremely rusty appearance of the whole ledge, indicating the presence of some iron mineral easily oxidized by the air. The surface of the ledge and of the fragments in the piles on either side is very rough and ragged, yet presents a certain regularity or banding in this raggedness. On examination we see that this is due to the uneven weathering or decay of the rock, some layers weathering away more rapidly, and thus leaving the others projecting irregularly and producing this uneven, rusty, ragged surface.

Let us now break into the rock to obtain a fresh surface for examination and study. The rock has a medium fine, granular texture, and presents many small, glistening, smooth, white surfaces telling us of the crystalline grains making up this rock. Something in the glistening of these grains makes us suspicious that these are not like those ordinarily seen in the rocks of this vicinity. We test them with the knife blade, and find them to be quite soft. We next put a drop of hydrochloric acid on the rock, and we are told by the effervescing, which is the escape of carbonic acid gas, that this rock is limestone; and by the many shining cleavage surfaces, that it is a crystalline limestone. Knowing this we now understand why this rock weathers so rapidly and so irregularly. The limestone is soluble in water, especially in water containing carbonic acid, and so the mineral substance of the rock is constantly carried away in solution by the waters coming in contact with it. But if we notice carefully we see that not all of the particles effervesce when touched by the acid. These latter particles are different in composition, and do not pass into solution in the water; hence where they are, the weathering of the rock surface is not so rapid. The projecting bands on the weathered surfaces are then due to these other minerals which are not so easily removed.

As we break into this rock in different parts of the ledge, we find that, however rusty it may be on the outside, it is free from rust at a short distance from the surface. We also find that there is considerable variation in the color of the fresh, unrusted rock; but taken as a whole it is of a grey color. But while noticing the color of the rock as a whole, we observe a variety of colors in the different grains. Let us carefully examine these under the magnifying glass.

Minerals in the limestone.

There is first the mineral of a light brassy color and metallic lustre, occurring in fine grains and distributed in every part of the rock. We instantly recognize it as iron pyrites. Its abundance, together with the ease and rapidity with which the limestone about it is removed, thus bringing it to the surface, explains the extremely rusty appearance of the rock and of the neighboring road.

Graphite in limestone.

We next notice some dark grey particles, at times a sixteenth of an inch or more in diameter. They shine with a metallic lustre, and are found to be very soft when touched with the knife blade. They are scratched

even by the finger nail. These particles are in the form of fine scales, and may be poked out by means of a pin. One of these scales, rubbed across the page of the note-book, leaves a mark like that of the graphite in the pencil. These are scales of graphite, and retain their lustre even in the rusty surfaces, because the agents of the air and water have no chemical effect on them. They point back to organic matter that was contained in this limestone before it was crystallized. In the crystallization of the minerals of the rock, the carbon contained in these substances was crystallized into graphite.

Actinolite in limestone.

But while looking at the graphite particles, we notice, because of its abundance, a light green mineral. It is sometimes granular and sometimes in the form of light green, glassy prisms or blades, which are best seen on weathered surfaces, and present more or less completely the outline of definite crystals. This is light green actinolite of the hornblende family.

Other minerals in the limestone.

In addition to these minerals, there may be found in this limestone a grey feldspar in rounded, cleavable particles, an half inch or so in diameter, completely surrounded by the limestone particles; and also a white feldspar in fine particles which remain after the carbonate of calcium has been dissolved by acid. There are, also, a reddish brown pyroxene, not easily recognized under the hand-glass, and small garnets and magnetite. From what has been said it is evident that this limestone is far from pure, but the rock is all the more interesting to us on that account.

Extent of this limestone.

But we may reasonably ask in regard to the extent of this limestone, for we are not accustomed to think of limestone as occurring in this vicinity. As a result of the examination of the neighboring ledges, we find that this limestone constitutes a narrow band, twenty feet or so in width, striking thirty-seven degrees east of north and dipping forty degrees west. This band may be traced to the southwest from where we first find it a short distance, and then we lose all trace of it. The limestone is only a local rock. On examining the rock in the ledges east and west, in which the limestone must be imbedded, we find it to be very like to the Bolton gneiss with its injected granite. In fact by studying the ledges of the intervening area, we may trace a direct connection

between these ledges in Millbury and those at the quarry near Quinsigamond. The ledges in these two somewhat distant localities belong to the same formation; and the rock-floor under the intervening territory consists of the Bolton gneiss. This limestone is evidently but a narrow band or thin layer in the Bolton gneiss, and was crystallized, with the formation of the included minerals, when that formation was crystallized out of sediments.

Other limestone areas in the Bolton gneiss.

But the Millbury limestone is not the only one in the Bolton gneiss. There is another one in Webster. It is situated a mile or so west of the great lake. In Northboro is another, near Ghost Hill. At this locality may be seen the remains of the old lime-kiln in which the limestone was once converted into lime. In Bolton is still another. This has been noted for a long time as a rich mineral locality. Near the centre of Boxboro, still farther to the north, is another. Here also is the old lime-kiln. Here are large masses of beautiful scapolite lying in the dump, thrown out as so much waste material.

Origin of the limestone.

As we have said, all of these limestone areas are within the region underlaid by the Bolton gneiss, and the limestone in each case is but local in extent. The limestone area is but a few hundred feet, at the most, in diameter. These limestone masses within the Bolton gneiss may represent deposits from calcareous springs. They form, however, a series of beds extending clear across the state and may have been more continuous formerly than now, and have been formed by the accumulation of organic remains. These deposits were afterwards recrystallized and the included minerals formed, when they and the surrounding rock were more or less deep beneath the earth's surface.

CHAPTER V.

SHREWSBURY DIKE.

While this is intended as a study of the rocks of Worcester, nevertheless, we have been led, more or less frequently, beyond the limits of the city, because of the extension of these rocks, and because geological phenomena are not limited by town boundaries. There is a small region just beyond the border of Worcester, included within the area of the Bolton gneiss, which will well repay our study. To this we next invite your attention.

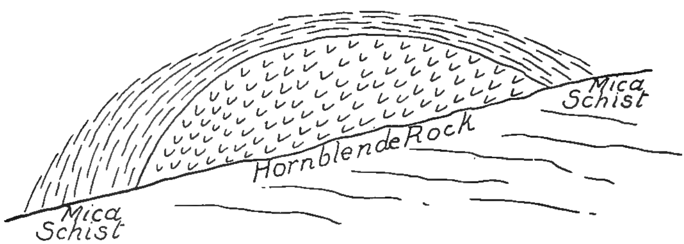
Taking the electric car for Shrewsbury, and having reached the eastern side of Lake Quinsigamond, we pass the cemetery on the right, and then, somewhat beyond, come to a road on the left. At this corner, we pass into the field at the northwest, and immediately find two quite different rocks. One is a rusty, thinly laminated mica schist containing the mineral fibrolite in small masses of shining, glassy needles. The other rock of this ledge is of a dark grey, almost black, color; is of a finely granular texture, massive in structure, and is cut irregularly by many joints into quite small angular blocks. Within, this rock has, in spite of its outwardly massive appearance, somewhat of a schistose structure due to the parallel arrangement of the mineral particles, producing a tendency to split in the direction of the arrangement. As we handle these pieces of rock, they seem to us heavier than similar pieces of average rock, and this makes known to us its somewhat high specific gravity. Under the magnifying glass we see that this rock is largely composed of one mineral, black in color and distributed in fine, blade-like crystals lying parallelly to each other, and thus producing the schist structure already noticed. This black mineral we recognize from its lustre and structure as black hornblende. Distributed among the particles of hornblende we see other particles, white in color and glassy in lustre. On weathered surfaces these white particles become dull white from decay, showing that they are feldspar; but they are

Rusty fibrolite schist.

Hornblende schist.

so fine that we cannot determine, by simply looking through the hand-glass, whether they are of orthoclase or of plagioclase feldspar. This rock, because of its schist structure, and because of the abundance of hornblende in it, may properly be called a hornblende schist.

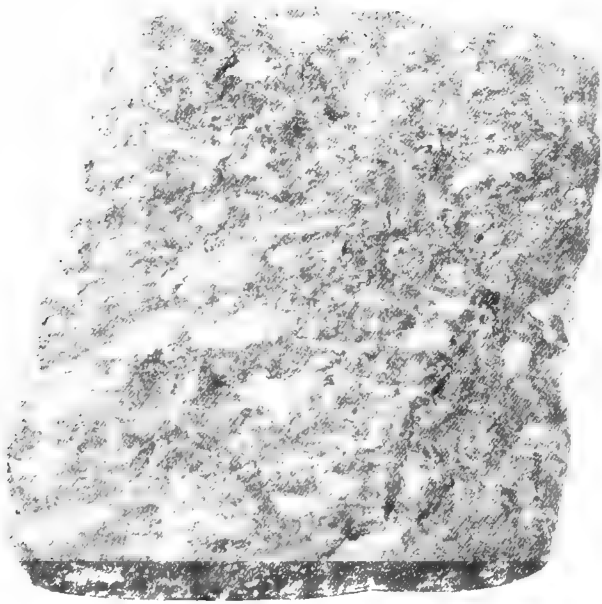
But in addition to this study of the rock itself, we must study its relation to the neighboring rusty mica schist found in the same ledge. We first determine the extent of the hornblende schist—that it is but a narrow mass, six to eight feet in width, with the rusty schist on either side of it, and wrapped over by the rusty schist above. The accompanying illustration shows the face of the ledge as it appears above the ground.



The hornblende schist varies in its structure, being generally very massive, in spite of the parallelism in the arrangement of the hornblende; but next to the rusty mica schist this massiveness gives place to a truly schist structure, the rock becoming even fissile, and the folia are parallel to the laminae of the mica schist. If one does not look carefully, he may think that one rock blends into the other; but the presence or absence of the hornblende serves to clearly indicate where one rock ends and the other begins. We here carefully study these two rocks, where we may observe them together and on such a small scale, that we may clearly see the relation of one to the other.

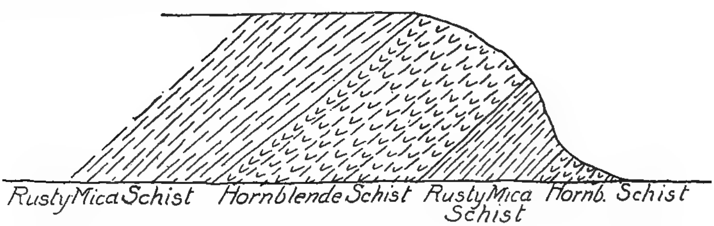
Second outcrop.

Seeing another outcrop to the northwest, and only seventy-five to one hundred feet away, we go to that. We find the same two kinds of rock, the massive, somewhat finely grained hornblende rock, cut into angular blocks by joints and fissures, and the thinly laminated rusty mica schist. But let us look for the relation which they bear to each other in position, as we did in the study at the other outcrop.



Diorite from Shrewsbury Dike. Original, 5 Inches by 4.

The western side of this outcrop is nearly vertical, and twelve to fifteen feet high; this affords us an excellent opportunity to determine the relative positions of these rocks. Starting at the base of the ledge, at the southern end, we find the finely grained, streaked, massive hornblende schist rising above the ground, three or four feet only, and sloping down to the north into the ground out of sight. Above this and resting on it, we find the rusty mica schist, six to eight feet thick, also sloping down to the north, parallel to the hornblende schist, and disappearing beneath the ground. Next above this mica schist, and also sloping down like the others, is another bed of hornblende schist of greater thickness than the others, and the last that we can see on the western side of the outcrop. On going up on this outcrop, and thence to the north, at a distance of a few feet, we come to more outcrops, all of rusty schist. If then we put the facts here presented into a drawing, they will appear in this way.



From this we see that the relative positions of these two rocks in this outcrop are quite different from what they were in the first outcrop but a few rods distant. Of the identity of the two rocks in one outcrop with those in the other there can be no doubt. Before trying to comprehend the full meaning of these facts, let us search for additional material to assist us in the study.

Third outcrop. Looking to the north we see, at but a short distance and under two large oak trees, a large outcrop. In this we find a massive hornblende rock. At first sight it appears quite different, because of its coarseness, from that hornblende rock found in the other two outcrops. It is of a dark grey color, blotched with white, and is cut by many joints or fissures into irregular, angular blocks. But little of the schist structure appears in it, though there is somewhat of parallelism in the arrangement of the coarse hornblende. On the weathered surfaces the horn-

Description of this phase of the hornblende rock.

blende frequently projects, showing that it is less rapidly removed by the air and water than is the material of the white blotches. These blotches are dull white in color, frequently oval in shape, an inch or more in diameter, and arranged so that the longer axis is parallel to the direction of the hornblende masses. We break into the rock to obtain a fresh surface for examination. The blotches are much less conspicuous here than on the weathered surfaces. The mineral constituting these blotches is in fine grains, which now and then show the cleavage surfaces of feldspar. They are, then, granulated crystals of feldspar, and probably indicate a crushing or shearing in this rock mass. Within some of these granulated feldspars may be seen very fine, olive green needles pointing approximately in the direction of the longer axis of the feldspar. These are needles of actinolite. All these facts indicate an arrangement of these minerals under pressure. We also examine the cleavage surfaces of the feldspar particles for striations, for these will prove that the feldspar is plagioclase and not orthoclase. We derive very little satisfaction from this search because the bright shining surfaces are so rarely seen. After much searching, we conclude that the cleavage surfaces do not show the striations, and so we are left in doubt whether this feldspar ma be orthoclase or plagioclase without the twinning which produces the striations; but from the basic composition of the rock we may expect the feldspar to be plagioclase. That this is so is proved by the ease with which it fuses and by its effect on polarized light. There are patches, also, somewhat abundant in places, of a brown colored mica. The hornblende and the triclinic feldspar are the essential minerals of this rock. It is then a diorite. When it contains the brown mica, it is a biotite diorite. The finer hornblende rock in the first two outcrops is simply this same rock having a finer texture.

Pyrrhotite in the diorite.

Thus far we have noticed only the essential minerals of this rock; but during our study we have very likely noticed a bronzy colored mineral in fine particles distributed through the mass of the rock in places. This is pyrrhotite, a sulphide of iron. With this may be seen a yellow, brassy colored mineral of metallic lustre also in small quantity and in grains. This is chalcopyrite or copper pyrites. Then there is also the common iron pyrites. But much more abundant than these, and occurring in

Chalcopyrite in the diorite.

Shrewsbury Dike. Ledge of Indurated Talc by Side of Road.

quite a different manner, is another mineral. It is found coating the surfaces of the rock, filling, or partially filling, certain joints by which the rock is cut. The mineral is white, and occurs in long, bladed crystals crossing each other so as to form a network on the surface. This is the mineral wernerite or scapolite, and quite pretty specimens have been found by breaking away the rock along some of these joints.

Scapolite as a secondary mineral in the diorite.

Still another mineral found here, but in smaller particles, is magnetite. The presence of this is made known by powdering some of the rock, and then putting the ends of the magnet in the powdered rock. The magnetite adheres to the ends of the magnet.

Magnetite in the diorite.

But here, as in the other outcrop, let us note the relation which the hornblende rock bears to the neighboring rock. The latter is the same rusty mica schist containing fibrolite, which was found in the other two outcrops; and here the rusty schist is found east and west of the hornblende rock. From this we are able to derive an idea of the width of the hornblende rock. It is from fifty to one hundred feet wide in different parts of this somewhat long outcrop.

But again, before trying to understand further in regard to this rock, let us determine whether we have found all that there is of it. Taking the direction in which it is most likely to be extended, we follow the adjacent road to the north, a few hundred yards, and come to another outcrop. Here the ledge is in the form of a knoll. Next to the road appears the bare, vertical surface of the ledge, about ten feet high, presenting an excellent opportunity for study. Going around this knoll, on the southwestern and western sides, we find, as before, the thinly laminated, rusty, fibrolitic mica schist leaning against the rock of the knoll. The latter rock is massive and without structure, of a dark grey or rusty grey color, and is cut by many joints into angular blocks. Its surface is more or less uneven, because of the unequal weathering. On attempting to break the rock, we find it not brittle, but tough and soft, yielding beneath the hammer. The fresh surface of the rock is of a dark grey color, of finely granular texture, and with almost no foliated or schist structure. As we handle the rock we notice a smooth, soapy feel,

Fourth outcrop of the hornblende rock.

Description of the rock of the fourth outcrop.

and find that the rock is easily and deeply scratched by the knife blade. Under the magnifying glass we see the great mass of the rock to be of a dark grey colored substance in which we may detect, now and then, a bright blade of hornblende, like that seen in the rock of the last two outcrops. Most of this dark grey substance is dull, or made up of glistening particles too fine to be distinguished under the glass. There are also small particles of a light green and olive green color, glassy in lustre, and soft enough to be easily scratched by a pin. Particles of magnetite may, now and then, be seen, of a dark grey color and bright metallic lustre. These may be separated from the rock substance by powdering the rock, and then stirring the powder with the ends of the magnet. In this way we find the magnetite quite abundant, while the coarse hornblende rock under the oak tree contains little of this mineral.

While the description just given applies to the great mass of the rock of this knoll, on breaking into it at different places we find considerable variation. At times the rock has somewhat of a schist structure, especially in the northern part of the ledge bordering the road. This variety has the same soapy feel, dark grey color, and softness. Under the glass we see in the midst of the dark grey, here and there, bright blades of hornblende, and the same light green mineral as before, but the schist surface has an irregular or knotted appearance, as if something were buried just beneath the surface. After considerable breaking of the rock we may succeed in finding that these little knots are produced by an inclosed particle of glassy lustre and amber color. This mineral proves to be olivine. There is still another mineral here, but it cannot be seen even under the magnifying glass. Its presence is made known by dropping a piece of the rock into hydrochloric acid. There may then be a slight effervescence, which becomes quite rapid on heating the acid. This is a characteristic of the mineral dolomite, showing that it is distributed in fine particles through this rock.

Olivine in fourth outcrop.

Dolomite in fourth outcrop.

We find here, also, a part of the rock, especially near the surface, of a light grey color, sometimes of a greenish grey, bordered on the weathered surface by a yellowish layer a quarter of an inch or more in thickness. Under the magnifying glass the massive, light grey rock is seen to be made up,

Tremolite.

in considerable part, of a finely fibrous mineral, the fibres in small converging masses, of a faint olive green, grey, or white color. This mineral is a form of tremolite. On the outside, where this mineral comes in contact with moisture and agents of air, the rock becomes yellowish in color, soft and soapy to the touch, though still remaining fibrous. These are characteristics of the mineral talc. Quite pretty, though small, specimens of fibrous talc may here be obtained.

Fibrous talc.

Rock of the fourth outcrop a massive talc.

We will now consider the rock of the knoll as a whole. The light green, soft mineral, found in the different specimens, is light green talc; the dark grey, massive part is also largely talc, containing blades of hornblende. The rock as a whole is then a massive talc. But it is of further interest because it presents to us several transitions. The meaning of the association of the hornblende and talc is that the former is in the process of change into the latter; the little particles of olivine, formerly distributed through the whole rock as we have found them in one specimen, have changed into light green talc; while carbonic acid from the air, together with magnesium and calcium from the hornblende or olivine, have formed dolomite; in part also the hornblende near the surface has changed to tremolite, and then the latter has further changed into a fibrous talc. From these statements it is evident that the rock is now quite different from what it originally was, the hornblende and olivine being the only minerals which we can consider as belonging to the original rock. The former serves to connect this ledge with the outcrops already studied a few hundred yards to the south.

Fifth outcrop.

But, again, we search in the neighboring fields for more ledges that may be connected with the line thus far traced. Going easterly across one field and into the next, under a large oak tree, a little to the south, we find ledges. In outward appearance the rock is very dark grey, in places almost black. The surface is uneven from unequal weathering, and presents a dull white mineral in irregular streaks, separating the small masses of a black mineral, the latter standing out on the surface. We break into the rock, and find the same coarse, black hornblende in bladed masses, with some hornblende of a light green color, and finely granular, glassy feldspar showing, now and then, a cleavage surface under the glass. Clearly this ledge

belongs with those already studied on the other side of the road.

Sixth outcrop.

Thence we go to another oak tree somewhat northeasterly, in the same field, and but a short distance, and there more of the hornblende rock appears; and then a little farther on, still more; then crossing a small brook and going towards the Shrewsbury road, still more; thence going on the Shrewsbury road and starting up the hill, perhaps one fourth the distance up, we come to an excellent cutting in the ledge made when the electric road was built. Here is a fresh surface ready for our study.

Seventh outcrop by the side of the Shrewsbury road.

We note first the marked schist structure, on account of which the rock has a smooth surface parallel to the road, which is here about north and south. This surface of the rock is almost vertical, dipping eighty degrees to the west. It also presents a marked streaked appearance, the streaks being so regular and long as to give one the impression of alternating white and black lines. These alternating lines pitch down to the north at an angle of fifty-five degrees from the horizontal. The black streaks prove, on examination, to be black hornblende, and the white show the finely granular, glassy feldspar with, now and then, an ungranulated particle in the midst. Again evidently we have found more of the coarse hornblende rock which, by outside pressure and shearing, has been given this schistose structure. On examining more of this ledge but a few feet from the road, we find that much of it is lacking in the schist structure, and in part, at least, is much more feldspathic. In spite of this there is no difficulty in considering it as belonging with the line of outcrops already found. We may here notice also a few narrow bands, of much lighter color, running through the midst of the hornblende rock. These are the edges of granite dikes. The granite is later than the hornblende rock, and simply fills fissures made in this rock at some time. We may also find on the surface of joints white blade-like crystals of wernerite or scapolite, exactly like those in the ledge under the first oak trees near the beginning of this line of outcrops.

Scapolite.

Rusty mica schist.

Another fact to be noticed here is the presence of the same rusty schist a short distance beyond, in the bank of the road. The meaning of this is that

this hornblende rock has no great width here; but the width is not so easily made out here as at the first outcrops, because of the loose earth covering the surrounding surfaces of the rock.

Eighth outcrop.

But again we continue our search, going up the road towards Shrewsbury, to the first road branching to the left; turning into the field at the right, we go to the top of the hill near some large trees, and there find outcrops. At first, just before reaching the top of the slope, we find the rusty mica schist, and then, but a few feet easterly, a dark grey massive rock, cut by many joints, in various directions, into irregular, sharply angular blocks. In spite of the massiveness we see a streakedness, even on weathered surfaces, telling of a schist structure within due to the parallel arrangement of the minerals. Breaking into it, we find the rock closely resembling the hornblende rock at the first two outcrops in this line. This, too, we may call a hornblende schist, being made up of the black hornblende and finely granular feldspar, which are arranged in parallel and irregularly alternating folia. These outcrops we put into the line of outcrops we are following. The limited extent of this rock to the west is indicated by the occurrence of the rusty mica schist but a few feet distant; probably the extent to the east is no greater. The hornblende rock is at the most but a few hundred feet wide.

Rusty schist.

Description of the rock of the eighth outcrop.

Ninth outcrop.

Leaving this locality and returning to the road where we left, we pass on to Mr. Moen's estate, taking a direction ten degrees west of north; at a distance of a quarter to a third of a mile we come to a ledge the rock of which is familiar in appearance. But on the way we must notice the rock seen in the ledges of the fields through which we pass. The ledges are quite numerous, and all are of the rusty, mica schist with which we have become so well acquainted.

The rock of the special ledge to which we have come is of a dark grey color, of mottled or blotched appearance. The blotches are of a dull, dirty white color, an inch or so along the longer diameter, and are roughly oval in shape, on a background of very dark grey. The surface of the ledge is more or less uneven, at times pitted, because of the unequal weathering. Breaking into the rock for a fresh surface, we see that the dark grey or black mineral is simply hornblende, in finely bladed masses, and the white is granular

feldspar. In fact this rock is identical with that seen in the third outcrop near the beginning of the line.

Tenth outcrop.

If we wish to follow farther, by going fifteen degrees west of north and an eighth of a mile, we may find still another outcrop of the hornblende schist type, identical with those already described.

Relation of these ten outcrops to each other.

It is evident from these descriptions that we have been dealing with rocks closely related though in separated outcrops. We notice also that these outcrops are narrow, and are bordered on either side by the rusty mica schist, which is found in a considerable area in the surrounding country; that these outcrops do not follow a line parallel with the strike of the laminae of the schist, but are in a zigzag, crossing this strike several times. It is evident, then, that this hornblende rock in these different outcrops does not constitute a bed or layer in the rusty schist, for then it would follow the strike. We must, then, consider this hornblende rock an eruptive which is also indicated by its composition and also by the facts observed in the first two outcrops. In the form of a molten rock it came into its present position. It is possible that all these outcrops constitute a single dike, and that the dike appears in these separated outcrops because of the loose earth which covers and hides the intervening parts of the dike. By this we mean that there was one fissure following the line we have traced, and into this the molten rock came, filling it, and there solidified. It is more probable, however, that these outcrops are offshoots from a considerable mass of this rock beneath, and that there is no surface connection between most of these outcrops. The meaning of this is that at some ancient geologic time, there rose from some greater depth in the earth a considerable mass of molten basic rock into the midst of this rusty mica schist, when the latter was far beneath the surface of the earth; from this larger mass of molten rock offshoots forced their way between various laminae of the schist; in due time the whole mass and offshoots cooled slowly and crystallized. After the crystallization, in the course of events, the schist and the inclosed eruptive rock were subjected to a common pressure or shearing, crushing the feldspars of the latter to granulated masses, and giving to it a marked schist structure parallel with that of the neighboring mica schist. Still later the joints were produced, cutting across the schist structure, possibly by the cooling down from the heated

condition produced by the shearing and crushing. Then as time went on, the surface of the earth above was gradually lowered by weathering and by the removal of the rock material by running waters, until the earth's surface reached the schist into which these offshoots of molten rock had penetrated, thus exposing them, separated by areas of rusty mica schist, but not exposing the larger mass of which they are offshoots, because the surface has, as yet, not gone quite low enough.

CHAPTER VI.

ROCKS IN THE BALLARD FIELD AT QUINSIGAMOND

AND

RELATION OF BOLTON GNEISS TO THE CARBONIFEROUS QUARTZITE.

Problem. Having now described and studied the rocks of the Ballard quarry, as representing the Bolton gneiss, together with the rocks of some areas of interest, also belonging to this formation, but not represented among the rocks of the quarry, we are led to seek for the relation that this Bolton gneiss bears to the Carboniferous rocks, which have already been studied, and which lie just west of it. If we can determine this relation, we may then assign this gneiss to its proper place in the historical sequence of the rocks of the earth.

Location. In seeking to determine this relation, let us go directly west from the Ballard quarry, through the fields north of Gibbs street. We find there many outcrops, and, in places, see alternating schist and granite bands beautifully and marvellously crumpled, showing that they have been subjected to a common north and south compression. In this study everything is perfectly clear as far west as the gulch, at the foot of which is a stone arch, over which is Gibbs street. Crossing this gulch, it is evident that we have reached a critical place, where we must carefully and closely study, if we would aright interpret the facts here presented. The critical area extends from this gulch west to Providence street, and north from Gibbs street across one field into the next, as far as any outcrop appears.

It will be necessary for us, first, to describe the rocks found in this area, as they of themselves are very interesting. In this description we begin with the rocks on the east side of Providence street, nearly opposite Doane street. The rock here has recently been cut into to furnish building stone, thus affording an excellent opportunity for its study. This rock is of a dark grey color, due to the abundance of

Granite of the Ballard field.

very dark brown biotite mica. This mineral is distributed in thin, long, narrow, blade-like masses, giving to the rock a streaked appearance. These mica masses are also parallel to each other, and so abundant that they give to the rock a marked foliation, parallel to the lamination in the neighboring schists. Because of this foliation, the rock easily splits into well-defined slabs. The foliation is in a plane extending nearly north and south, and nearly vertically. The foliation has a dip of eighty-five degrees to the west. As we walk over the surface of the ledge, we are stepping on the edges of these folia. The other minerals of the rock are quartz and feldspar, so finely granular that they are not to be distinguished from each other by the unaided eye. Under the magnifying glass we may see particles of quartz somewhat larger than the average and slightly tinted. The whole appearance is of a rock that has been severely crushed and sheared, granulating the quartz and feldspar, and arranging the mica in blades, giving to the rock a foliated, almost schistose, structure. That this rock is a granite is indicated by the position it occupies relative to the neighboring rocks, and by its position. That it is younger than the quartzite, found in the field nearby, is made evident by its containing inclusions of that quartzite in the most northerly outcrop, a little north of the eastern end of Upsala street. An inclusion of the Carboniferous mica schist is also found in this granite; the latter is then younger than the schist. The eastern boundary of this granite is quite accurately indicated, because the outcrops are numerous; but the western border is uncertain, because the rock-floor is almost completely covered by till from Providence street to Vernon street, where the Carboniferous phyllite appears. On the south, the boundary of this granite is concealed by the sands of the Blackstone, and, on the north, by a thick covering of till. While we cannot make out accurately the bounds of this granite, we are certain that it has no great extension. It is simply a local rock, but has a character of its own. It is a distinct variety of granite found within the borders of Worcester.

Aplite dikes in the granite.

On the surface of the ledge opposite Doane street are seen light colored, narrow bands, that contrast with the darker granite. The rock of these is nearly white in color; is partly finely granular and partly coarsely granular in texture, and consists largely of triclinic feldspar, as is indicated by the many striated cleavage surfaces. This rock is also musco-

vitic in part; and all of it has a shimmering of muscovite or sericite on the surfaces of the folia, which are parallel to the sides of the bands. In it may be found a light cinnamon-colored garnet, and apatite of a light green color in considerable, though not well defined, crystals. This rock is an aplite, and bears the same relation to this granite that the aplite, in the dikes of Millstone Hill, did to that granite.

Glacial marks on granite. On the surface of this granite may be found glacial scratches pointing five degrees west of south.

Dike of hornblendic rock in granite. In this granite is also found a rock which appears with the granite on west side of Providence street, as well as on the east. This rock appears in a somewhat wide band, and, at a glance, is seen to be quite different from either the granite or the aplite already studied. It is of a dark green, or dark greenish grey, color; is fibrous, or finely bladed, in texture; and has a foliated structure because of the arrangement of the blades in parallel planes, producing an indistinct cleavage. The fresh surface of the rock is marked by brownish spots, more or less irregular, and half an inch, or more, in diameter. Even by the unaided eye the dark green, almost black, blades are recognized as hornblende, while the brownish spots are seen to consist of dark brown biotite. So large a part of this rock is made up of these two minerals, that we do not at first see any other, and may think it a massive hornblende; but under the glass we find a white, glassy mineral, which also shows on the weathered surfaces. This is a feldspar. This rock also constitutes a dike in the midst of this granite, and is later than it. What time relation the hornblende rock bears to the aplite does not appear, as the two rocks were not seen touching each other.

Outcrops of hornblendic rock in neighboring fields. This dark green rock is closely related to the rock appearing in other outcrops in the neighboring fields just east, and it is well for us to study the rock of these outcrops at this time. One of these outcrops may be found on either side of Gibbs street, five hundred to five hundred and fifty feet from Providence street; another in a small, narrow, elliptical area, two hundred feet, or so, southwest of the southwest corner of the pond in the field; west of the southern end of the same pond is another outcrop of the same rock, constituting a long, narrow strip, but a few feet

Pitted Surface of Diorite from Ballard's Field, Near Quinsigamond. Original, 7 Inches by 4.

wide, and two hundred to three hundred feet long; again in the next field, north, is a circular area of the same rock, constituting a knoll, one hundred and fifty feet, or so, in diameter.

Outward appearance of the diorite.

In these different localities, the rock is essentially the same, though varying in texture, being coarser in one and finer in another, and varying in the relative abundance of the different minerals. It may be studied to the best advantage in the most northerly of these outcrops. Here the rock is of a rusty grey color on the weathered surface, and somewhat speckled in appearance, because of the difference in color of the two important minerals. It is perfectly massive, without sign of foliation; but it is cut by many joints, extending in different directions, into irregular, angular blocks. In places, also, the weathered surface is deeply pitted, presenting an appearance that quickly attracts the eye. This indicates that the minerals in this rock are not acted on and removed uniformly by the agents of the atmosphere.

On attempting to break this rock for a fresh surface to study, we find it exceedingly tough; and we also find that the rusting has extended far into the rock, following the joints, and penetrating the rock from these. Because of these facts, and also on account of the absence of foliation, it is difficult to obtain a nicely shaped specimen presenting fresh surfaces.

Appearance of the diorite on a fresh surface.

Within, this rock is of a dark grey, in places, greenish grey, color; of crystalline, granular texture, sometimes coarse and sometimes fine, and is without order or uniformity in the arrangement of its minerals. Under the magnifying glass, we pick out the different minerals. There are iron pyrites and magnetic pyrites, marked by their colors and lustre. They, in part, at least, account for the rusting of this rock, which has already been noticed. There is the white mineral, some of it slightly tinted grey, glassy or waxy in lustre, and, now and then, presenting cleavage surfaces, showing the fine striations characteristic of a triclinic feldspar. With ease we identify the hornblende, bladed in structure, and partly dark green, and partly light green in color. Then there are the brown blotches, which are seen to be made up of brown biotite mica. We observe that these blotches are just about as numerous on a fresh surface, as are the cavities producing the pitted appearance on the weathered surface. In fact the biotite

masses, distributed through this rock, weather or decay, under the action of the atmosphere, more rapidly than do the other minerals, and so produce the pitting on the weathered surfaces. With much searching we may also find, in this rock, a mineral, glassy in lustre, having a slight rosy tint, and so hard as to be but slightly, if at all, scratched by the knife blade. This mineral may sometimes be found in particles, even a half inch through. This mineral is garnet.

Garnet in diorite.

If we study this rock in its other outcrops, we shall find it always practically the same, composed of hornblende and triclinic feldspar, with clumps of brown biotite distributed through it. The rock is a biotite diorite.

Occurrence of the biotite diorite on the Heywood farm.

But this diorite is not limited to these two fields. If the covering of till were removed from the hill to the north and northeast, we should find other outcrops of it. Back of the barn on the Heywood farm, which is on the north side of this hill, may be found more of this rock, presenting the same pitted surfaces, and having the same composition. The abundance and wide distribution of the fragments of this rock in the neighboring stone wall indicate that there is a large area of it here, perhaps even larger than the area on the Ballard estate.

Relation of these outcrops of biotite diorite to each other.

Putting together the different occurrences of this diorite in this field, east of Providence street and on the Heywood farm, we see that it bears no fixed relation to the neighboring rocks. Sometimes it occurs in schist, and sometimes in granite. Moreover there is no visible connection between these different areas. Each one is, so far as we can see, entirely surrounded by another kind of rock. If we study this rock carefully, especially west of the south end of the pond in this field, we shall find evidence that this rock is an eruptive rock. When in a molten condition, it came up into the midst of these other rocks, filling the fissures, and there crystallized.[1] It differs from the granite in that it is a basic eruptive, while the granite is an acid eruptive. But while there may be no visible connection between these different outcrops of the diorite, there is probably a connection beneath. They all really came from one mass of molten rock, the larger part of which solidified beneath the rocks which are now at the surface. The garnets, which we have seen

[1] It is possible that this diorite is a continuation of the Shrewsbury dike of diorite which was considered in Chapter V.

in the diorite, were possibly derived from the neighboring garnetiferous mica schist, through which the molten rock came into its present position.

Garnetiferous hornblende granite.

A third rock within this area, and of interest for us, is found in a knoll between the first area of the foliated granite and the small pond to the east. This rock, on the weathered surface, is of a slightly rusty grey color; is massive, without foliation or schist structure, but is cut by joints, in various directions, into angular, irregular blocks. The weathered surface is marked by irregular spots of a pink color, one half inch or more in diameter, the material of which stands out in relief, indicating unequal weathering of the surface. These spots distinguish this rock from the neighboring rock. On breaking, the rock proves to be very tough; at the same time, the pieces fly with great force under the blow of the hammer, making evident its brittleness and strength. The rock is hard and compact, and presents a quite well defined conchoidal fracture. It is of a dark grey color on the fresh surface, of medium fine, granular texture, and shows nothing of a schistose structure. There appear, dotting these surfaces, light pink glassy blotches one half inch or more in diameter, of irregular, rounded shape, which are granular masses of a pink garnet. These garnets add much beauty to specimens of this rock.

Under the magnifying glass, we may see a considerable quantity of dark brown mica, in bright shining scales, and also mica of a full black color. There are quartz of a smoky color, and glassy, colorless feldspar, recognized by its cleavage surfaces. In addition, a green hornblende particle may, now and then, be recognized. But the larger part of the rock is a fine, granular, dark grey mixture, in which it is not easy to distinguish the separate minerals. Here and there, black mica may bė seen; but how much of the mixture may be black hornblende cannot be determined under the hand glass.

This rock is clearly distinguished from the schistose granite already described, situated just east, by entire want of foliated structure, and difference in composition; on the other hand, it differs from the diorite in containing much quartz, little hornblende, much more mica, and many garnets. It must be remembered that we found in the diorite a few, irregular, small masses of granular garnet. As a rock this is best described by calling it a garnetiferous, hornblende, biotite granite; but if it is related to any of

the neighboring rocks, it is to the diorite rather than to the schistose granite. This garnetiferous granite is also an eruptive rock. It is found in an area only about thirty feet in diameter. We may see in it, in addition to the minerals already noted, pyrrhotite, recognized by its bronzy color, and metallic lustre, and by being attracted by the magnet. There are, also, iron pyrites and some magnetite, the latter in fine particles, and found only by powdering the rock, and picking out the particles by means of the magnet. Their color distinguishes them from the pyrrhotite. These ores are sufficiently abundant to materially increase the specific gravity of the rock.

Metamorphic rocks of the Ballard field.

By these eruptive rocks, very interesting in themselves, we have been led away from the problem which was presented to us,—the relation of the Bolton gneiss to the Carboniferous rocks already studied in previous chapters. These eruptives do not help us at all in solving the problem: they tend, by their presence and effect on the neighboring rock, to make this solution more difficult. We must now study the rocks of this area that were here before either granite or diorite came into their midst.

The mica schist of Ballard field.

There are two of these rocks. The first, nearer Providence street, appears in many outcrops. It is a mica schist. In some outcrops it is exceedingly rusty; and the iron pyrites, producing this effect, may frequently be seen within the fresh rock. Where not rusty, the rock is of a light grey color; in part, it is thinly fissile, and, in part, is quite massive, or appears so, before breaking. This massive variety is seen at the corner of Gibbs and Providence streets. It is a light grey mica schist, almost silvery in lustre, containing only a little biotite. In its different outcrops, it contains various minerals, as pink and yellowish garnets, fibrolite, and andalusite. In places, also, graphite gives to this rock a dark grey color and noticeably greasy feel. This schist was made out of ancient sediments, and is older than the eruptives already described. They were forced from beneath into its midst. This schist is, then, one of the connecting links between the Bolton gneiss on the east and the Carboniferous rocks on the west.

Micaceous quartzite in Ballard field.

In going across this field to the east, we encounter still another rock at the foot of the small pond. This is of a medium fine, granular texture, of grey, or rusty grey, color, and of laminated structure.

Under the glass a part of the laminae are seen to be composed, largely, of glassy, granular quartz, slightly rusty; the remainder of the laminae contain much, somewhat coarse, black, or dark brown, mica, causing these laminae to be much darker than the others. In addition there is some feldspar in these laminae, as is indicated by the dull white color of some particles on the weathered surfaces. This rock is also garnetiferous. These alternating light and dark laminae, frequently only a small fraction of an inch thick, are not arranged regularly with the general dip and strike of the rock, but are intricately folded, crumpled, and faulted, so that a single lamina cannot be traced with certainty more than a short distance. Because of this, the dip and strike are not easily determined. This rock, from its constituent minerals, may be called a micaceous quartzite. It may be traced, by outcrops, to the north and south for a short distance. It constitutes a narrow band, one hundred to two hundred feet wide, east of the schist just studied. Within the micaceous quartzite may be found narrow dikes of granite, which is partly fine, and partly coarse, grained. This quartzite does not extend east as far as the Bolton gneiss.

Mica schist between Bolton gneiss and micaceous quartzite.

Between the last rock studied and the Bolton gneiss is more mica schist. This is also of a light grey color, almost silvery, and, in places, somewhat rusty; is generally thinly laminated, but, in part, is apparently massive; has something of a smooth, soapy feel; abounds in garnets, and is sometimes fibrolitic; and it contains a light grey mica, with but little biotite. On placing specimens of this schist, side by side, with specimens from the schist west of the micaceous quartzite, we can see no difference. We are forced to believe these schists, east and west of the micaceous quartzite, one and the same. This schist extends east to the Bolton gneiss. The data that we must use in the solution of our original problem are before us.

In considering this we are led to ask: What relation does the micaceous quartzite bear to the schist in whose midst it occurs? To answer this question, we must carefully examine the contact, or the line, where the quartzite joins the schist on the east and on the west. Fortunately for our study these lines are fairly well exposed in the most southern part of the field, near Gibbs street. There we may see the quartzite laminae dipping west,

and down, under the laminae of the schist; at the eastern contact we likewise see the laminae of the schist dipping down under the quartzite. In one case quartzite dips beneath schist; in the other, schist dips beneath quartzite. These two facts of themselves do not help us in determining which is the upper and which is the lower formation, but tell us that there is here a compressed and overturned fold.

Relation of the micaceous quartzite to the mica schist.

To make clear the last sentence, let us consider Figure 1.[1] There is a compressed synclinal fold on the left, and a compressed anticlinal fold on the right, and both are tipped over to the right. One side of each fold is parallel with the other side of the same fold, and these sides differ in direction only at the top and bottom of the fold where the sides curve towards each other. There are included in these two folds two different bands distinguished by the markings. That marked 1–2, 3–6 and 4–6 is one band, and, if the folds were unfolded horizontally across the page, that band would be above the other marked 2–7, 7–3 and 4–5. That the former band is the upper is clear even in the folds, because we see the whole of the folds.

Figure 2 is simply a reproduction of the lower part of Fig. 1, with all above the line A B in Fig. 1 omitted. In this figure it is easy to see that the band 1–2, 3–6, 6–4 is the upper band, because we see the bottom of the left hand fold, and can easily supply from the figure above the part of the curve that is lacking. If now, as in Fig. 3, we reproduce only a section from Fig. 2, omitting the lower and upper part of the curve, we can readily see, by comparing it with the other two figures, exactly what part of those figures is reproduced and that marked 1–2, 6–3 is the upper band.

But if Figures 1 and 2 were not on the page to indicate the relation of the bands 1–b and 3–d, it is evident that the bands might be joined below by continuing and curving the boundary 1a around to join 6d, and 2b to join 3c. This figure would then represent a compressed synclinal fold. In that case the band 1–b, 6–c would be the lower band, and the band 7–b, 7–c would be the upper. If, on the other hand, the boundaries a–1, b–2 are continued above the figure and curved to join, respectively, the boundaries d–6, c–3, the bands will then constitute an anticlinal compressed fold. In this case the band 1–b, 6–c would be the upper band resting on the band 7–b, 7–c.

[1] Page 125.

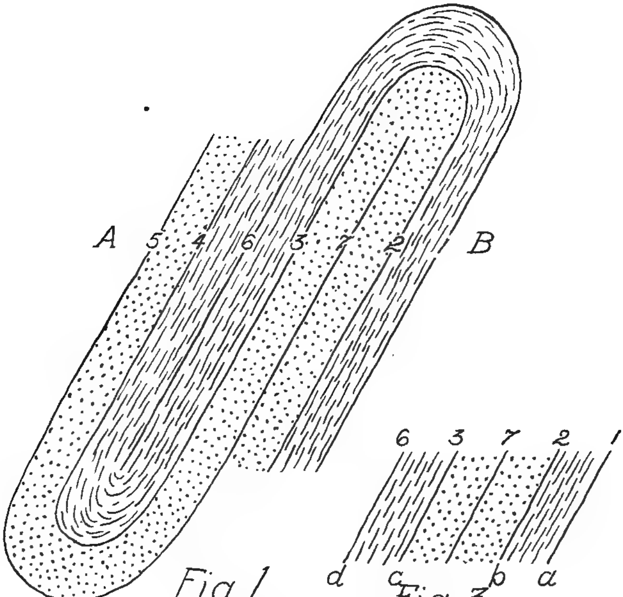


Fig. 1. Fig. 3

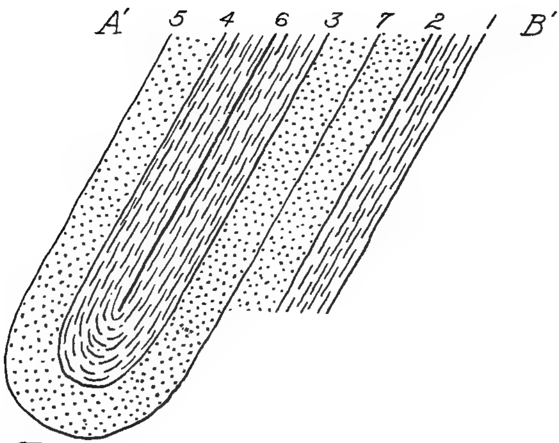
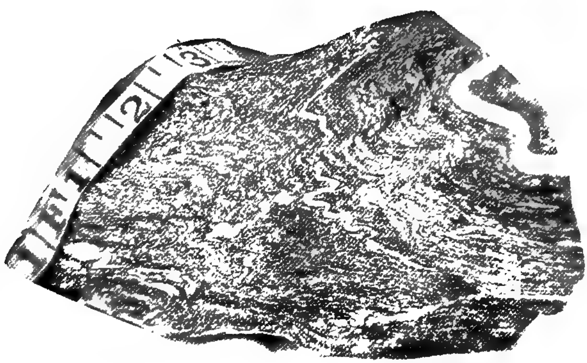


Fig. 2

From this discussion, it is seen that the bands 1–b, 6–c become the lower or upper band according to whether they are joined beneath into a synclinal or above into an anticlinal fold. There is nothing in Fig. 3 to tell us which is the correct drawing, if this figure is considered independently of Figs. 1 and 2. Let it be noticed, also, in Fig. 3 that the band 1–b dips under the band 7–b; while the band 6–c, corresponding to 1–b, leans against 7–c corresponding to 7–b. In one case the first band dips under the second; in the other the second dips under the first. From this it is evident that their relative positions tell us nothing as to which may really be the upper or the lower band.

Let us now compare the conditions presented in Fig. 3 with the facts presented by the mica schist and quartzite in the field just north of Gibbs street. We must first bear in mind that this land surface has been subjected to great erosion so that it is made up of only remnants of formations. We must not expect facts to be presented in their entirety. On the west the micaceous quartz dips beneath the mica schist, and on the east the schist dips beneath the quartzite. We cannot see beneath the surface to determine whether or no the schist extends down below the quartzite and joins the schist on the other side; neither can we determine from what remains whether or no the schist bands formerly joined above the quartzite. Our only hope in such compressed folds is in finding the end of the fold where we may see the curve in the beds by which we shall know whether the beds curve down in a syncline or up in an anticline. As the mica schist on either side does not help us, the micaceous quartzite must be carefully studied. Unfortunately for this study, its laminae have been so crumpled and faulted in this ledge, that a single lamina can with difficulty be traced only a few feet at the most, to say nothing of tracing the same lamina from one side of the outcrop to the other. We are forced to abandon our study at this ledge, but we have clearly in mind, from the study made here, exactly that for which we must look. Let us, then, examine the next outcrop, north, of the quartzite, which presents to us the rock surface represented in the opposite picture. This shows us clearly the centre of an anticlinal fold. But the difficulty with this is that we cannot be certain that it is the centre of a large anticlinal fold including the whole of the quartzite. It may be only a small anticline, constituting a secondary fold on either a large anticline or a large

An Anticline in Micaceous Quartzite in Ballard's Field, Near Quinsigamond.



Crumpled Laminae of the Micaceous Quartzite, Found at Quinsigamond.

syncline. This is, however, the best that we can find in this outcrop, because the crumpling and faulting have been so severe as to obliterate, conceal or confuse the lines of lamination.

Keeping this small anticline in mind, as a starting point, we go still farther north to the outcrop south of the pond, where we have already studied. After careful study and examination of the southern end of this outcrop, we may see laminae of the east side of this outcrop slanting or dipping easterly; on the west side of the same outcrop the laminae are dipping westerly. Going around to the northern side of this outcrop, we may there see the laminae arching over from west to east in an anticlinal fold, whose top slants down to the north. The geologist expresses this by saying that the fold pitches north. Here, fortunately for our study, the fold is not compressed, as is the fold a little farther south, but is here an open, anticlinal fold. Having found that this quartzite is in the form of an anticline, we are now able to understand the relation it bears to the schist occurring on either side of it. The quartzite extends beneath the schist and was folded into an arch up into the midst of the schist; then as erosion lowered the surface of the earth by removing the rocks above, this quartzite, in the form of an arch, came to be exposed with the schist on either side of it. The quartzite is therefore beneath, and is the older rock of these two.

Mica schist and micaceous quartzite Carboniferous.

But this micaceous quartzite is a well defined rock, and one that is not easily mistaken. We have already become well acquainted with it in Wigwam Hill. Between these two localities, there are intervening outcrops, showing clearly that the two are one rock, and connected. From Wigwam Hill we may directly trace, by a series of outcrops, this folded micaceous quartzite to the deep cut of the B. & A. R. R., at the bridge where Plantation street crosses the railroad. Here this same micaceous quartzite appears in the midst of the Carboniferous phyllite. Here the quartzite is folded or faulted up into the Carboniferous phyllite in a manner, probably, similar to that in which the quartzite is folded up into the mica schist in the field on the Ballard estate at Quinsigamond. In other words the micaceous quartzite at Quinsigamond is the Carboniferous quartzite, and the mica schist on either side of it, being above it, is really only the Carboniferous phyllite in a little more highly metamorphosed condition.

That this conclusion is correct, is made clear by finding, in this silvery schist in this field at Quinsigamond, small areas of schist that cannot be distinguished from the regular Carboniferous phyllite, as it is found at the deep cut of the B. & A. R. R. There is a very thin strip of regular Carboniferous phyllite included in the schistose granite by the side of Providence street, and this is on the side of the granite towards the silvery schist that we have been studying, and very close to the latter. Just east of the garnetiferous granite is a graphitic phyllite so closely resembling much of the regular Carboniferous, that the two cannot be distinguished; again, on the very border of the Bolton gneiss, is more of the schist that is not to be distinguished from the Carboniferous. To repeat, for the sake of emphasis, we may conclude that the light grey, somewhat rusty, mica schist, between what we had before identified as Carboniferous and the Bolton gneiss, is also Carboniferous, metamorphosed one degree more highly by the granite within its midst, and by the granite possibly beneath it. We have thus traced the Carboniferous formation to the very border of the Bolton gneiss.

Relation of Bolton gneiss to Carboniferous rocks.

It now remains for us to consider the relation of the Carboniferous schist to the Bolton gneiss, and thus determine the position of the latter in the historical series. The best place for our study is at the head of this gulch, which Gibbs street crosses by means of a stone bridge, for there are many outcrops where these two rocks approach each other. Starting with outcrops west of the head of the gulch, which are clearly of the light grey, silvery Carboniferous mica schist, we go east, constantly breaking off specimens for study, and at the same time noting the direction and dip of the laminae. After passing a few hundred feet east of the gulch, we notice that the rock has now come to be largely the gneissoid granite, which was so abundant at the Ballard quarry. We are now on the Bolton gneiss. At some point we crossed the line between the two. In passing from one to the other no change is noticed in the dip or the strike. The laminae of one are parallel with those of the other. There is, however, a great increase noticed in the quantity of granite that has been injected between the laminae, as soon as we get on the gneiss. While a little granite may be seen in both the silvery, grey schist and in the micaceous quartzite to the west, here in the Bolton gneiss fully one half of the rock is granite. This granite is foliated

parallelly with the laminae of the schist bands inclosing it, and the bands of each show a crumpling in common. But let us compare the grey, silvery schist, west of the gulch, with the schist of the bands alternating with the granite in the Bolton gneiss. The former is highly muscovitic, with a very small proportion of granular quartz; while the latter is biotitic, and contains a much larger proportion of granular quartz. These schists are not the same; yet the uniformity of dip and strike points to a close relationship.

Comparing mica schist of Bolton gneiss with the micaceous quartzite.

In comparing different specimens we may, perchance, compare some of the specimens of the biotite schist from the Bolton gneiss, near the head of the gulch, with specimens of the micaceous quartzite at the foot of the pond, a little to the west. A marked resemblance is immediately seen. Each is abundantly biotitic; each is very sandy, or made up largely of glassy, granular quartz; each is made up of the thin light and dark alternating bands, severely crumpled. The only difference between the two is that the schist from the Bolton gneiss has more granite material soaked into it. We therefore conclude, after a careful study, that the alternating schist bands of the Bolton gneiss are simply bands of the micaceous quartzite, a little more highly metamorphosed through the influence of the large proportion of injected granite between the laminae. But the micaceous quartzite has already been traced into such close relationship with the Carboniferous schist or phyllite that the quartzite can only be considered as Carboniferous. The schist of the Bolton gneiss, being the same as the micaceous quartzite, must then also be considered as Carboniferous. In the historical series the Bolton gneiss constitutes a part of the Carboniferous of Central Massachusetts. It is the micaceous quartzite made gneissoid by the abundant injection of granite between its laminae.

CHAPTER VII.

Paxton and Brimfield Schists.

Location.

Having now carried our study of the rock-floor to the eastern boundary of Worcester and beyond, let us retrace our steps, and go to the west. We have already studied the Carboniferous quartzite as it occurs in Pleasant street near Newton square, and at the foot of Chadwick street; and we naturally inquire in regard to the western extension of this formation. Let us then go out through Pleasant street towards Tatnuck, being constantly on the watch for outcropping ledges to tell us of the underlying rock-floor. Unfortunately for us in this study and search, the drumlins are very abundant in this area, and effectually conceal the underlying rock. We do not find any ledge until we have passed Tatnuck, and have begun to ascend the hill on the way to Paxton. Just before reaching the watering trough, after crossing Tatnuck brook, we notice on the left, or south side of the road, a good outcrop. Here we find two kinds of rock in the same ledge. The one is a coarse, crystalline rock, more or less rusty in color. In this we recognize the coarse feldspar particles by their cleavage surfaces and their porcelain-like lustre, and the quartz by its glassy lustre, want of cleavage, and its hardness; and, distributed through this mixture of feldspar and quartz, we recognize black prisms of tourmaline by their resinous lustre and shape. This part of the ledge is a tourmaline granite; and, as in the case of the other granites already studied, is later or newer than the rock in which it is included, and into which it was injected. This other rock gives evidence of having been disturbed as the granite was forced into its midst, for its layers or laminae have been bent out of their normal position so as to make room for the granite between them. Hence, as we take the strike, we find a considerable variation in the direction of the laminae, as they curve around the irregular granite masses. The strike varies from eight degrees east of north to fifteen degrees west of north; while the dip

Tourmaline granite.

Quartzose mica schist.

BANDED PAXTON SCHIST. SIZE OF ORIGINAL, 6 INCHES BY 5.

is from fifty to fifty-five degrees towards the west. This laminated rock is the original rock, and is worthy of careful study; but as there is not much of it here, and as it is more or less weathered, and we may find difficulty in obtaining good specimens for study, let us delay the careful study of it until we reach a quarry in this same rock, somewhat recently opened, farther up on this hill.

Tatnuck hill quarry.

This quarry is also on the south side of the road, and is a short distance west of the road leading from the Paxton road to the Tatnuck Country Club house. The first fact to attract our attention, as we enter the quarry, is the perfection of the lamination. On account of this the rock breaks into thin slabs, especially near the surface of the ledge. These slabs are frequently half an inch, or even less, in thickness, but as the depth increases, the slabs become thicker, so that those removed from the bottom of the quarry may be a few feet in thickness. From this we conclude that the final separation of this rock into very thin slabs is due to frost and other weathering agents, acting along planes of weakness that are already in the rock. Extending nearly vertically and easterly and westerly, and also northerly and southerly, are two sets of cross-joints which may be distinctly traced in different parts of the quarry. These joints cross the planes of lamination obliquely, and give to the slabs a rhombohedral form. So smooth and well-defined are these surfaces, that they remind us of those produced by crystalline cleavage. The lamination planes result from the arrangement of crystalline particles; and the separation of the rock-mass into sheet units is due to the original layers in which this material was deposited by water before it was solidified or cemented. The cross-joints are due to tension within the rock-mass, probably produced by the folding to which this rock has been subjected.

Description of the mica schist of the quarry.

But let us study the rock itself, for here is an excellent opportunity on account of the freshness of the specimens. A large part of the rock of the quarry is of a brownish grey color, with here and there a greenish tinge, having an indistinct banding generally parallel to the lamination. It has a medium fine, granular texture. Examining it under the glass, we see that the brownish tint is due to brownish mica, distributed abundantly in fine scales parallel to each other and to the lamination of the rock. The splitting of the rock is due, in part at least, to this arrangement of these mica

scales. The remainder of this rock is a finely granular mass of glassy particles, some of which glisten with cleavage surfaces indicating feldspar, while others are simply particles of quartz. In addition to these we find distributed irregularly and in clumps, and associated with small, thin masses of a mixture of feldspar and quartz, hornblende, sometimes of a light green color, and sometimes of a dark green, sometimes granular, and sometimes in small bladed crystals. This rock is, then, largely a mixture of fine granular quartz and brown mica; it is a mica schist.

Variation in Paxton schist.

A considerable part of this schist has a marked banded appearance. This banding is due to alternating layers of brownish and greenish grey, the greenish bands being much lighter in color. These bands are frequently a quarter of an inch or less in thickness, at other times an inch or even more. The dividing lines between these bands are, in some cases, clear-cut and sharply defined; in other cases, the bands blend into each other. The brownish bands are identical with the schist already described; the greenish bands are lighter from the absence of the brown mica, and have, in place of it, a fine green hornblende. On searching these greenish bands carefully, we observe little, amber colored crystals distributed, here and there, but most abundantly with the coarse, dark green hornblende. These amber colored particles are probably little garnets. In other respects the greenish bands are like the brownish, and may be called bands of hornblende schist. This banding of the rock, with the abundance of quartz in it, tells us of the former condition of this rock, when it was in the form of impure sands deposited by the waters of an ancient sea. The brownish bands were layers which contained a little more clay, and the green, or hornblendic, bands contained more iron rust. Since the time when they were layers of sand deposited along the shores of an ancient ocean, they have been buried deeply in the earth, and recrystallized, just as the rocks in the Quinsigamond quarry have been recrystallized. Because of the abundance of this mixture of mica and hornblende schists in the ledges of the neighboring town of Paxton the mixture may be called the Paxton schist.

Tourmaline granite in Tatnuck hill quarry.

But to return to the study of the rock of this quarry—we find still another rock. It is nearly white in color, and hence attracts our attention. It occurs without any regularity in position, and in

Tourmaline Granite in Paxton Schist. Size of Original Specimen, 6 Inches by 4. From Quarry South of Paxton Road.

more or less nodular-like dikes or masses, cutting across the bands of the schist. At other times the bands of the schist wrap around the nodular masses. In other words there is no fixed relation which the white rock and the schist bear to each other. The masses of the white rock vary greatly in size—sometimes a foot, sometimes several feet, through; sometimes these masses are connected, sometimes separate and distinct. We examine the rock itself. It is sometimes fine and sometimes coarse. The same mass frequently shows this variation from fine to coarse, being fine around the border, where in contact with the schist, and coarse in the centre. From the manner in which the rock occurs, and from the minerals which it contains, we recognize it as a granite. It was evidently forced or intruded into the midst of the schist, while the schist was in a yielding condition, for the schist frequently folded and bent without fracture; and, even when the granite cuts across the laminae of the schist, the break was more like that in a soft, pasty substance, than that in a hard, brittle mass. The intrusion of the granite may be associated with the period of recrystallization of the schist, though the variation in the size of the grains of the granite indicates that the granite came in contact with surfaces somewhat cool, producing a more rapid crystallization around the border, and hence finer granular texture next to the schist.

In this granite we recognize the feldspar by its pearly white cleavage surfaces. This is nearly all orthoclase feldspar, for it is difficult to find a striated surface indicating a triclinic feldspar. The coarser feldspar is frequently not pure white, but of a slightly greyish tint. The quartz is also white, but is more glassy, and lacks the smooth cleavage surfaces. Besides these minerals this granite uniformly contains black, columnar crystals of tourmaline, the prisms varying considerably in size, and showing the characteristic resinous lustre and grooved sides. The almost complete absence of mica in this granite attracts our attention; the tourmaline seems to take its place. We also note that frequently the tourmaline is not uniformly distributed, but is condensed around the border next to the schist. Because of the abundance of the tourmaline, this granite may rightly be called a tourmaline granite.

Garnetiferous tourmaline granite.

In some of this granite, especially the finer grained, we may find little, light pink garnets. The faces on these crystals are not clearly marked, so we cannot

make out the exact mathematical form of the crystals. This granite, with its tourmaline and garnets, marks a distinct variety not before met with in our study of the rocks of Worcester, and we take a specimen of it to represent this variety of rock.

Edge of the plateau of Central Massachusetts.

Before leaving the quarry, we must observe the dip and strike of the laminae of the schist, to help us in placing it in its proper position with reference to the other rocks studied in the rock-floor. We find the laminae striking or pointing almost exactly north and south, and dipping about thirty degrees to the west. In other words, as we ascend this hill, which is really the edge of the plateau of Central Massachusetts, we are walking up, or across, the edges of these upturned laminae which are sloping down into the hill to the west. The strike may be best taken up on the surface of the ledge where the rock has not been quarried.

Glacial marks.

Here, also, we may see the glacial scratches nicely preserved on the surfaces of the granite masses that are imbedded in the schist. Undoubtedly these scratches were made over the whole surface, on the schist as well as on the granite, but the weathering or crumbling of the surface of the schist has been sufficient to remove them. We also take their direction and find that they point five to ten degrees east of south. Comparing this direction with those found in the eastern part of the city we may conclude that the ice of the Glacial Period moved in an almost southerly direction with a slight deviation to the east.

Other minerals in this quarry.

In addition to the minerals already mentioned, there may be found in this quarry iron pyrites in fine particles, in both the schist and the granite; the surface of one slab was covered with a thin coating of stilbite crystals. The indications are that this quarry will afford but few minerals, and will not compare in this respect with the quarry at Quinsigamond.

As the laminae of the Paxton schist of the quarry point nearly north and south, we may expect to find it extending in those directions; and so we cross the fields to the south seeking for traces of it. We find it in outcrops north of the next road, Fowler street, leading from Tatnuck up the edge of the plateau to the Lynde Brook Reservoir. The same rock appears in numerous outcrops on the side hill south of this road. There the laminae strike nearly

north and south, deviating only five to ten degrees east of north, and dip forty degrees to the west.

Granite area south of Fowler street.

As we follow Fowler street up the hill, near the top on the east slope, we notice, on the south side of the road, and in the road, a rock constituting a ledge, yet evidently not the schist which we are following. From its general resemblance to the granite already seen at the quarry, we may surmise that it is more granite within the schist. Careful study confirms this. As in other cases, we break off several pieces for examination. This rock is of a grey color, and of a medium fine, granular texture. It has a noticeable foliation parallel to the lamination of the neighboring schist. There are many glistening scales of white mica or muscovite, of darker mica of a brownish color, and of black mica or biotite. There are, then, two, if not three, kinds of mica present in this rock. The quartz and feldspar generally make up a fine granular, sugary mixture, in which may be distinguished with difficulty the two minerals; but, here and there, a coarser particle, now of glassy quartz and now of feldspar, appears. By examining several of the latter, we may find one showing the striated surface of triclinic feldspar. We therefore conclude that both orthoclase and plagioclase feldspars are present in this granite. The foliated structure of the rock, together with the finely granular condition of the quartz and feldspar, indicates that this rock has undergone a severe crushing by which these minerals were pulverized and arranged with a parallelism of position, giving a foliation and fissility to the rock. This granite is clearly distinguished from the small, tourmaline granite masses seen at the quarry to the north. Tourmaline is almost entirely lacking in this granite. In only one place do we find it, and then on the border of the schist, and in small quantity. This granite also contains two or three micas, where that rarely contained one; and this contains more triclinic feldspar. As we look about us, we see this granite extending quite a distance to the south, and so we follow the outcrops, that we may represent on the map the area under which the granite extends. Before we are through tracing its boundaries by means of the outcrops, we conclude that this granite constitutes quite a large mass, yet somewhat smaller than that of Millstone Hill. This granite extends south to the house of the late A. Swan Brown; to the west, to the top of the hill, and a few hundred feet west of the house

there; and to the north, under the loose glacial material, some distance, though exactly how far cannot be definitely determined from lack of outcrops. This granite may then be represented on the map as an oval area, a mile and one eighth in length by about a quarter of a mile in width.

Granite widely distributed in Paxton schist.

This is only one of the many granite areas found within this Paxton schist, as the schist is traced from town to town, for it is the rock seen at the surface in broad areas to the west in the plateau of Central Massachusetts. But frequently the granite in this schist is in much smaller masses, at times being but a few feet in thickness, and constituting bands that alternate with bands of the schist. These granite bands tell us of the rising from beneath of molten rock, while the schist was far beneath the surface, separating the strata of the sedimentary, or the laminae of the recrystallized rock, and forming sheet-like masses between them. In other cases the molten rock was intruded in larger bodies and widely separated the strata or laminae. In these different positions the molten rock slowly crystallized, constituting the granite sheets and areas now found within this schist.

Extension of the Paxton schist to the south.

If we continue our study to the south, we shall find in the outcrops this same mixture of Paxton schist and granite extending under Cherry Valley, then appearing in a cut by the side of the railroad then west of Jamesville, and farther south outcropping frequently in Auburn, Oxford and Dudley, but always lying to the west of the Carboniferous quartzite, which we have studied in the second chapter. But this Paxton schist, mixed with granite, does not constitute a narrow band just west of the Carboniferous quartzite; it extends over a broad area, underlying many towns, to the west, in Central Massachusetts.

Extension of Paxton schist to the north.

Returning to the quarry on the side of Tatnuck Hill, from which we started in our study to the south, let us in like manner study to the north. We may find the same schist at the Cascade. This succession of waterfalls is produced, in part, by the water of this brook flowing over the edges of the laminae of this Paxton schist. Here these laminae point about north and south, and have a small dip of twenty-five degrees to the west. Thence we may trace this schist along the Holden Reservoir road into Holden, and on to the north,

until it disappears under an overlying formation. Throughout this extent, the schist, or the granite belonging with it, is adjacent to, and west of the Carboniferous quartzite, the two occupying the same relative positions to the north that they do to the south.

Relation of Paxton schist to Carboniferous quartzite.

We are next led to inquire what relation the Paxton schist and Carboniferous quartzite really bear to each other. To solve this problem, let us go out on Chandler street to a point a short distance west of the junction with Hadwen lane. There, on the northeast side of the street, may be found a large outcrop presenting the fresh rock.

Ledge by side of Chandler street near Hadwen lane.

Even at a distance we notice the laminated structure, because the edges of the laminae point directly towards the street. They strike twelve degrees east of north, and dip fifty-two degrees west. The rock is of a grey color with a brownish tint; is of finely granular texture; consists largely of very fine, glassy quartz, mingled with considerable fine brown mica, which gives a brownish tint to the whole rock. If we compare this rock with that in Pleasant street, west of Newton square, or with that at the foot of Chadwick street, we shall instantly conclude that all these rocks are one and the same formation. This idea is confirmed by the strike of the laminae in the Chandler street ledge, for they are pointing almost directly across to those in Pleasant street. We therefore conclude that we are still on the Carboniferous quartzite.

Tourmaline granite in quartzite by the side of Chandler street.

But while we are at the ledge by the side of Chandler street, we may notice, in the midst of the quartzite, a rock, nearly white in color, which does not conform to the laminae, but is wrapped around by them. In structure this white rock is massive, and cut by joints into irregular, angular blocks, varying in size. In texture it is largely finely granular, becoming, in places, quite coarse. We immediately recognize in it the colorless, glassy quartz, and the white, porcelain-like feldspar. The latter is, in part, quite coarse, and has a grey color. Mica is almost entirely absent. There are, however, fine, columnar crystals, approximately parallel in position, distributed through this rock. These little crystals have a resinous lustre, and a brownish yellow, or dark amber, color. They prove to be, on testing, little crystals of tourmaline. This white rock is a small intruded or injected mass of tourmaline granite in the Carboniferous quartzite. The occurrence of this

tourmaline granite here reminds us of the tourmaline granite found in the Paxton schist, at the quarry near the Paxton road.

Apatite in tourmaline granite of Chandler street.

While studying this granite, our attention is attracted by little deep-green particles, distributed, here and there, in it. These particles are generally longer than they are thick, indicating a prismatic shape; and they have a glassy lustre, and are not so hard but they may be scratched by the knife blade. On being tested, they are found to dissolve in nitric acid, and this solution gives a decided test for phosphoric acid. These characteristics clearly indicate that this mineral is a deep-green apatite.

Study of the ledge in Mill street near June.

In our study of the rocks by the side of Chandler street, we have, perhaps, forgotten the object in view. We wish to determine the relation of the Carboniferous micaceous quartzite to the Paxton schist. From Chandler street we will seek other outcrops nearer the Paxton schist. Unfortunately, the drumlins in the western part of Worcester are unusually abundant, and securely conceal the rock-floor over large areas. We go through June street to the west, because we shall then be going directly towards the Paxton schist. We do not find an outcrop until we reach Mill street. Just south of the junction of these two streets is a large ledge appearing by the side of the street, and presenting the freshly broken rock for our study. Other outcrops may be found in the neighboring fields, on the west of Mill street.

Description of the rock by the side of Mill street.

The rock of these ledges is of a dirty grey color on weathered surfaces, and thinly laminated in structure. The laminae strike eighteen degrees east of north, and dip thirty-seven degrees west. The rock is dense and hard, and, under the hammer, breaks with a roughly conchoidal fracture. It is also somewhat tough and quite brittle. On the freshly broken surface, the rock is seen to be finely granular in texture, and of a brownish grey color. This rock is a little more decidedly brownish than was the Chandler street rock. This Mill street rock consists largely of finely granular quartz, mixed with a fine, brown mica. The mica is more abundant than it was in the Chandler street rock, hence the darker color; but is not more abundant than is the mica in much of the Carboniferous quartzite. The latter rock, as it appeared in East Kendall street, was quite as micaceous. The Mill street rock is also a

little coarser in texture than the Chandler street rock. In addition to the quartz and mica, the Mill street rock also contains disconnected, small masses, or irregular veins, of granite, more or less flattened, or lengthened, in the direction of the laminae. This granite frequently contains black tourmaline. Associated with the granite, though not really belonging to it, is a coarse, dark-green hornblende, in small bladed masses. These latter characteristics are identical with those of the rock in Tatnuck Hill, especially with those of the rock in the quarry near the Paxton road.

In texture this Mill street rock is finer than the Paxton schist. In other words, the rock we are now studying has characteristics connecting it with the Paxton schist to the west, and other characteristics connecting it with the Carboniferous micaceous quartzite on the east. It is the transition link between the two.

Paxton schist a coarser phase of the Carboniferous micaceous quartzite.

The outcome of this study is that the Paxton schist is only a coarser variety of the Carboniferous quartzite, coarser because more highly metamorphosed, and more thoroughly recrystallized. But we may reasonably ask why one has thus been more thoroughly recrystallized and metamorphosed. We have noticed, as we worked towards the west in tracing this connection, that there was an increasing quantity of injected granite in the schist. Near by, in the top of Tatnuck Hill, is a large area of granite. To the west in the plateau, wherever the Paxton schist is found, it contains more or less injected granite. To this injected granite, and to the probably greater masses buried beneath, from which these dikes at the surface are offshoots, we may attribute the greater metamorphism in the Paxton schist. A like effect was produced by the granite of Millstone Hill in the Carboniferous micaceous quartzite in East Kendall street.

Paxton schist and Bolton gneiss equivalents.

But we have already traced a like transition from the Carboniferous micaceous quartzite, on the east, into Bolton gneiss. The Paxton schist and the Bolton gneiss are, then, equivalents or simply parts of one extensive formation. Studying these two, separated by many miles, the geologist can not but note the many resemblances between them. The Paxton schist has been described as a quartzose mica schist, of a brownish grey color, and frequently containing alternating lighter bands of a greenish color. In the quarry

at Quinsigamond[1] the schist is, in large part, made up of alternating bands of brown and light green. So closely do specimens from the Quinsigamond and Tatnuck Hill quarries resemble each other, that they might reasonably be considered as coming from the same quarry. The resemblance extends even to the light green bands in each, containing small, light amber colored garnets. The Paxton schist and Bolton gneiss also resemble each other in containing a vast quantity of parallelly injected granite. Sometimes this granite appears in dikes a few inches thick, between the laminae; sometimes it is in the form of batholites a mile or more in width. The granite in one formation generally resembles that in the other. Each is a coarse granite containing much coarse, white feldspar, which occurs in large, rounded, flattened, cleavable individuals, rather than in distinct, porphyritic crystals. These granites are generally foliated parallelly to the lamination of the schist, giving a marked gneissoid structure. When the injected granite does not form a continuous dike, the coarser mica laminae wrap around the flattened feldspars producing a pseudo-conglomerate. The pseudo-conglomerate is quite as characteristic of the Paxton schist, as it is of the Bolton gneiss, and may be seen in perfection in outcrops near the dam of the Holden Reservoir, and in the large ledges near the Charlton station of the Boston and Albany railroad.

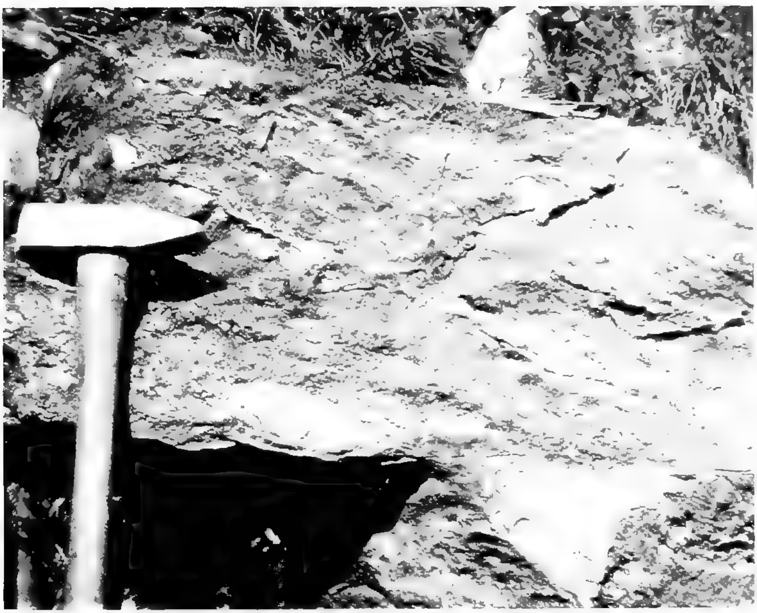
Pseudo-conglomerate of Paxton schist.

Difference between Paxton schist and Bolton gneiss.

But while there are these marked resemblances between the Bolton gneiss and Paxton schist, there is one marked difference. The Bolton gneiss contains many bands of a coarse, black, thinly laminated mica schist, more or less chloritic. This mica schist is rarely, if ever, found in the Paxton schist. While the Paxton schist was made out of layers of impure sand by a partial recrystallization, the Bolton gneiss was in part made from such layers, and in part from layers that were more nearly pure clay. This difference simply indicates that the original sediments to the west were more sandy, and to the east, more clayey. The more clayey sediments indicate more quiet and deeper waters, in which the sediments were laid down.

Another difference between the Paxton schist and the Bolton gneiss is that there are no limestone areas in the former like those in the latter. This, however, is a difference of minor importance,

[1] Ballard quarry.



Pseudo-metamorphic Conglomerate, from near Charlton Station of B. & A. R. R. From the Paxton Schist.

for the limestone in the Bolton gneiss is, perhaps, only accidental. It is possibly limestone that was deposited from calcareous springs rather than limestone formed from organic remains. There is in these differences nothing to prevent our thinking of these two rocks as equivalents or parts of one extensive formation.

Brimfield Schist.

Before leaving the extreme western part of Worcester, there is still another formation demanding our attention. If, on leaving the quarry near the Paxton road, we go west, instead of south or north, we shall soon find evidence that we are on quite a different rock. This rock may be best studied in the large ledges about an eighth of a mile west of the quarry, and back of the barn belonging to Homer King. At the eastern foot of the hill, made up of this new rock, will be seen the Paxton schist, striking seven degrees east of north, and dipping twenty-five degrees west. The laminae of this schist slope down into the base of this hill beneath the new rock.

Let us now study and describe this, the last of the rocks constituting any considerable part of the rock-floor of Worcester. While this rock underlies only a few square miles in Worcester, it makes up the whole of the rock-floor under some of the neighboring towns to the west and northwest. It is an extensive formation, though not so important in Worcester.

Brimfield schist described.

The first characteristic of this new rock is its extremely rusty color. It is everywhere charged with iron rust. The predominating mineral which gives special character to the rock is mica, generally reddish in color, but in places white and silvery. While the mica is quite generally in flat scales, as wide as long, sometimes these scales have the appearance of having been drawn out, or lengthened, in the direction of the strike, so as to present an almost fibrous form. Because of the parallelism in the arrangement of the mica scales the rock has a marked lamination, and splits along planes parallel to the scales. Frequently also the laminae of the rock have been crumpled, developing more or less secondary cleavage, so that the splitting of the rock is in places quite irregular. In addition to the mica, this rock contains considerable finely granular quartz, partly rusty, and partly white and glassy. Mixed with the quartz is some

feldspar, also granular and rusty or white. These are the essential minerals of this rock. Because the mica predominates and gives special character to the rock, the rock is rightly called a mica schist. But as the extreme rustiness is also characteristic, it may be called a rusty mica schist. Because of the occurrence of this rusty schist in the rock-floor of the town of Brimfield it has been called the Brimfield schist.

Minerals in Brimfield schist. Before considering this rusty schist in its wider relations, let us examine it more closely for other minerals. At first we find very little to reward our search, but after a time we may find a mineral occurring in white, or slightly rusty, small masses or clumps, made up of fine glassy fibres. It is the mineral fibrolite or sillimanite, which we have already described as occurring in a mica schist at the red bridge over the B. & A. R. R., near Bloomingdale, and in the rusty schist that was associated with the Shrewsbury diorite. While searching for the fibrolite, we may possibly notice fine scales of a dark grey color, shining with a metallic lustre. They are scales of graphite. In the midst of this rusty area is a mass of coarse tourmaline granite; in the schist bordering this granite may be found little black prisms of tourmaline. These have been developed, probably, in the schist by its contact with the granite. These are the minerals noticed in this rusty mica schist at this place, though garnets are frequently found in it elsewhere.

Extension of the Brimfield schist. We may next inquire as to the extent of this rusty schist. We follow this ledge south through this field and into the next. The loose glacial material covers the ledges until we have crossed Fowler street. As we have already pointed out, only the Paxton schist and granite appear south of this street; then, evidently, this rusty schist does not extend far south of where we see it in this ledge already studied. To the north, however, we may find it at the Cascade where the uppermost laminae, over which the water falls, are of this rusty schist. Thence we may accurately trace, by means of the numerous outcrops, the boundary line between the rusty Brimfield and the Paxton schists into Holden. This line is found west of the road[1] extending from Tatnuck northwesterly by the side of the Holden Reservoir. This boundary is indicated on the geological map. West of that line, for many miles, the surface rock is the rusty mica schist, containing larger or smaller masses of intruded

[1] Olean street.

granite. Such is the rock of Asnebumskit, rising fourteen hundred feet above the sea, and four hundred feet above the surrounding plateau.

Relation of the Brimfield and Paxton schists in Tatnuck hill.

Having studied this rusty Brimfield schist as to minerals contained and as to extent, we may inquire what relation it bears to the Paxton schist, to which it is adjacent. In the hill where we studied the rusty schist, we saw the Paxton schist at the eastern foot, striking seven degrees east of north and dipping twenty-five degrees west. In other words the Paxton schist dips, or slants, down beneath the rusty schist, which is in the upper part of the hill. At first thought we might conclude that this settles, once for all, the relation of these two rocks, and that the Brimfield schist must, of necessity, be above, or rest on, the Paxton schist. But it must be borne in mind that we are in a region where the rock strata have been folded to the superlative degree, and the rock substance frequently rearranged, producing secondary, if not even tertiary, structure, thus hiding the original structure or bedding. There are large and small folds. There are anticlinal, or arch-shaped folds, and synclinal, or trough-shaped folds. The folds may be open, their sides spread apart, or they may be compressed and overturned—their sides pressed together so that the laminae in one side are parallel with those in the other, and then the whole fold tipped over so that all the laminae slope in one direction except at the very top or bottom of the fold. Where such severe folding has taken place, it does not necessarily follow that, because the Paxton schist dips under the rusty Brimfield schist in one place, the former was really beneath the latter in their original positions.[1] These relative positions may have resulted from the overturning of a fold, thus causing that which was beneath to be above and resting on the originally upper one. If we could trace out the whole of a fold here, we might determine the relation of these two rocks; but this we are not able to do, partly because of the limited area of the exposed rock, and partly because of the confusion of structures within the rusty schist.

Relation of Brimfield and Paxton schists at the Cascade.

We therefore seek another locality where these rocks may be seen near to each other. They appear again together at the Cascade. This is situated west of Olean and Cataract streets and about one third of a mile north of Liberty Farm. Here a small brook

[1] See the discussion in regard to rocks in Ballard field, pp. 124, 125, 126, 127.

flows down the lower, precipitous edge of the plateau, constituting a series of small water falls, called the Cascade. The precipitous slope consists of the projecting edges of the laminae of the rocks of the plateau.

Commencing, in our study, at the foot of the Cascade, we find the Paxton schist in its well defined, slab-like laminae, striking about north, and dipping twenty-five degrees west. As we climb the steep slope, constantly examining the rock of the laminae, we find only the Paxton schist, until we have ascended two thirds, or three quarters, of the way, when we begin to find an alternation of the Paxton and rusty Brimfield schists. Then the proportion of the latter increases until, at the top of the slope, the rock is practically all rusty Brimfield schist. Again the Paxton schist is dipping beneath the Brimfield schist, and seems to blend into it, with no well defined line between. This blending or alternation may mean a change from sandy layers of deposition to clayey layers, when these beds were deposited in the waters of an ancient sea; or, possibly, this alternation may result from a minute interfolding or intercrumpling of the laminae of these two rocks along the border between them. If the former of these ideas is true, then clearly the Paxton is now beneath the Brimfield schist and possibly represents the older sediments, and is the older formation. But if the second idea is the correct one, then the relative positions mean nothing, and do not determine for us the actual relation of these two rocks. Which of these ideas may really represent the truth, we have not found possible to determine at this locality. Again we are left in doubt in regard to the absolute relation of these two rocks.

And so we may follow along to the north on this boundary between the Paxton and Brimfield schists, which is a crooked line lying west of Olean street, without solving this question, because nowhere does enough of a fold show to make the true relation of these two formations clear.

Remnants of Brimfield schist.

In an area where profound erosion has taken place, as there has here in Central Massachusetts, it sometimes happens that mere remnants of a formation have been left as detached areas. Such remnants, being small in extent and on a small scale, sometimes clearly present facts that may be concealed and overlooked in broader areas. Let us seek out one of these remnants in this study.

The Cascade, One-third Mile North of Liberty Farm.

Remnant in hillside at end of North Bend street.

We must return to Tatnuck, and follow North Bend street to its northern extremity; up on the high side hill to the northeast we see many ledges. As we ascend the slope, we at first find ledges which we unhesitatingly identify as belonging to the Paxton schist. To find the Paxton schist here is what we might rightly expect, for all along Olean street, on the western side of Tatnuck brook, we find this same schist except at the northern end of Cataract street, where we find the Brimfield schist extending as far east as Olean street. But on going a little higher on this side hill, and but a few hundred feet to the north, we observe a sudden change in the appearance of the rock. The rock is now a rusty, thinly fissile, muscovitic and biotitic schist badly crumpled into fine folds, and containing many wavy quartz veins and considerable included granite. In general outward appearance this rock closely resembles the Brimfield schist, and leads us to look for the two minerals, graphite and fibrolite, so characteristic of that schist. We may be obliged to search some time for those minerals for they are not everywhere abundant here; but by persevering, the graphite may be found here, and, a little farther to the north, this same rusty schist is highly fibrolitic. This schist has all the marks of the Brimfield schist, though it is not, as far as we can see from this point, directly connected with the Brimfield schist on the other side of Tatnuck brook, a mile or two distant. Moreover on studying the ledges in an easterly direction we find that this rusty schist is of small extent in that direction, appearing only in the next field, with the Paxton schist east of it. The Brimfield schist is here only a few hundred yards wide, for it is made up of laminae pointing northerly; and the rock-floor is well exposed in broad areas showing the Paxton and Brimfield schists near to each other.

Position of schists in this hillside.

This is, then, an excellent place in which to study the relation of these two rocks. We therefore carefully take the dip and strike of the laminae of both schists in different parts of this hill. In the western part of the Brimfield schist the laminae strike 20–25° east of north and dip northwesterly; in the extreme eastern part of the same schist the laminae strike northwesterly and dip northeasterly. The Paxton schist is found in this hill, west and south and east of the Brimfield schist; in the western part, striking northeasterly and dipping northwest; in the southern part striking east and west and dipping

north ten to fifteen degrees; and in the eastern part, striking northwesterly and dipping northeasterly.

Illustration to explain the position of these schists.

Putting these observations together, the meaning thereof is apparent. Place a book, having a paper cover, flat on the table and lengthwise north and south; raise the southern end of the book so that the upper surface of the book is an inclined plane sloping fifteen degrees to the north; press the east and west edges of the book towards each other, bending the leaves up into a fold with the convexity up; now while you hold the book thus bent, let some one, with a sharp knife, cut along a horizontal plane through the leaves, thus removing the part of the book above this plane. If, now, we look at the edges of the leaves in this horizontal plane (what remains of the book being bent as at first) we see the leaves in the western part of the folded book pointing or striking northeasterly and dipping or slanting down northwesterly; in the eastern part, the leaves striking northwesterly and dipping northeasterly; and along the central line, extending north and south through the plane produced by the cutting, the leaves striking east and west and dipping north.

Relative positions of these two schists.

The observations on the position of the leaves of this book tally exactly with the observations on the laminae of the two schists in this side hill. The position of the leaves exactly represents the position of the laminae. The laminae of these schists are, then, bent into an anticlinal (convexity upward) fold, whose axis or topmost line is not horizontal, but inclined ten to fifteen degrees to the north; and this fold has been in part cut away by the agents of erosion during geologic ages. This fold is not overturned or compressed; it is an open anticlinal fold. The rock that is beneath in this fold is the one that was originally beneath. We are thus able to determine the original relative positions of these two schists at this place, because we see the top together with a little of each side of this fold.

In the southern part of this hill the Paxton schist strikes east and west and dips north down under the Brimfield schist. The former makes up the lower part of this fold, and hence is the lower of these two rocks.

On the opposite, or western, side of Tatnuck brook, these schists strike between north and northeast and dip northwesterly and are in the western side of this fold, showing that this fold, of which

we now see a small remnant, was a broad and extensive fold. Tatnuck brook valley has been cut in the western side of this fold, and has been cut through the Brimfield schist down into the Paxton schist.

Thickness of Brimfield schist in this side hill.

This last fact shows us that in this area the Brimfield schist is thin and is measured in depth by only a few feet or few hundred feet at the most. This, however, gives us no idea of the original thickness of this formation or of its thickness in other places, because in this anticlinal the Brimfield schist grows thinner and thinner as the folded laminae slant up to the south.

Small anticlines in this side hill.

We have now solved the problem that led us to this side hill, but there are other facts here worthy of notice. In the second field, to the east, is a large outcrop of Brimfield schist, whose southern end is marked by two large white pine trees. In this outcrop, within a width of one hundred feet or less, may be traced the laminae striking northeasterly and dipping northwesterly, striking east and west and dipping northerly, finally, in the eastern part of the ledge, striking northwesterly and dipping northeasterly. Again about three hundred feet northwest of this, there may be traced another small anticlinal fold also pitching or sloping to the north. These are small folds produced during the formation of the large fold, by the crumpling of the rock laminae near the axis or central line of the larger fold.

Tourmaline granite in these schists.

In both of the schists of this locality we find much intruded granite, coarse in the central part, and frequently fine near the border of the mass. This granite is white but contains black tourmaline, frequently in large prisms in the coarse granite, but in fine ones near the contact with the schist. In places these little tourmalines are so abundant as to cause the granite to be black. From such masses of tourmaline granite have come the many bowlders of tourmaline granite found in the more southern part of Worcester.

Faults in this side hill.

But there is a still more interesting fact brought out clearly in this side hill. Probably in our study, in this field, of the relation of these two schists, we have noticed that the Paxton schist, found to the east of the Brimfield, while striking northwesterly and dipping northeasterly, is at a considerably higher level in the hill than is the Brimfield. If,

also, we follow this eastern line of Paxton schist by outcrops to the northwest along the line of strike, for a quarter of a mile or so, we may also find the Brimfield, just west and dipping northeasterly, apparently sloping directly beneath the Paxton schist. This observation does not at all invalidate the conclusion as to which rock is really the lower one. The anticline is too clear and convincing. This apparent dipping of the upper beneath the lower schist indicates that more than simple folding has here taken place. The rocks have been broken, and the line of breaking had a northwest-southeast direction; the rocks on the northeast side of this line were raised or elevated so as to bring a part of the Paxton up on a level with, and even to a higher level than, a part of the Brimfield which is on the southwest side of this fracture. This observation serves to reveal to us a fault in the eastern side of this large fold.

This fault is probably not the only one in this anticline, for as we follow and study this narrow area of Brimfield schist to the north, there is evidence that this schist does not thicken as rapidly as might be expected from the northern slope or pitch of this anticlinal fold. A mile or so north, the Brimfield is evidently thin for the Paxton may be found in places in its midst as if the lower schist had been exposed by the wearing off of the upper. This failure in the Brimfield schist to thicken with the pitch of the anticline may be explained by supposing other faults crossing this anticline, and thus bringing the Paxton schist nearer to the surface to be exposed more readily by erosion. The meaning of this is that this anticlinal fold, instead of being made up of continuous rock laminae, has been broken into a succession of blocks of rock, and each block has been moved up a little, or elevated, with reference to the next block to the south, and then the whole surface worn down by subsequent erosion nearly to, or in places fully to, the boundary plane between the Paxton and Brimfield schists, thus sometimes exposing the former in the midst of the latter.

Age of Brimfield schist.

Before leaving this interesting area we must notice that this anticline has shown to us more than simply the relative positions of these two schists. We have already identified the Paxton schist as a more metamorphosed, or highly crystallized, phase of the Carboniferous quartzite, and is therefore Carboniferous in geologic age. The Brimfield schist lies above the Paxton schist just as the Worcester phyllite lies above

the Carboniferous quartzite; then the Brimfield schist, made from clayey sediments, corresponds to, or is a more highly metamorphosed phase of, the Worcester phyllite, and is therefore Carboniferous in age.

Paxton and Brimfield schists, the rocks of the plateau of Central Massachusetts.

We have thus far written of the Paxton and Brimfield schists as local rocks; they are much more than this. But a small part of these formations is contained, as has been intimated, within the bounds of Worcester. These two rocks, with their included granite, constitute nearly the whole of the plateau of Central Massachusetts, from Worcester to the Connecticut valley. Over this broad area the distribution of the Brimfield schist is somewhat irregular. While the great mass of it occurs in extensive areas, overlying the Paxton schist, there are many small areas, like that already studied, frequently constituting less than a square mile of surface, entirely isolated and surrounded by the Paxton schist. They, too, are probably remnants of this formation. They tell us of a much larger former extension of this Brimfield schist. It very likely covered the Paxton schist throughout the latter's extent, but has been removed over broad areas, exposing the underlying schist, by the profound erosion, by which the surface of the plateau of Central Massachusetts was produced.

Scattered areas of Brimfield schist in the Bolton gneiss.

In these scattered areas of rusty Brimfield schist, surrounded by the Paxton, we find something closely resembling what we also find east of Worcester in the Bolton gneiss. In the latter are isolated areas of a rusty, fibrolitic, graphitic, mica schist identical in appearance with the Brimfield schist. We have already noticed one such area bordering the Shrewsbury diorite dike; we have studied another area, east of Providence street, which shows a transition of the Carboniferous phyllite into this rusty schist, and which also shows its relation to the Carboniferous quartzite, that of an overlying, conformable formation. Numerous other areas of this rusty schist might be pointed out in the neighboring towns through which the Bolton gneiss extends. All these confirm the belief that the Brimfield schist is above the Paxton in the plateau west of Worcester, and is the equivalent of the Carboniferous phyllite.

Graphite mine at Sturbridge.

With the Carboniferous age of these rocks of Central Massachusetts so well established, the old graphite mine at Sturbridge, which has been sporadically worked for so many years, comes into its proper place. Like the graphite deposit here in Worcester, that deposit is of the Carboniferous, and represents an ancient vegetable deposit, now entirely recrystallized into graphite. In like manner the graphite, which is found in fine scales almost everywhere in the Brimfield schist, also represents organic matter buried in these clayey beds, when they were deposited in that distant geologic time.

Looking Across the Plateau of Central Massachusetts.

CHAPTER VIII.

General Geology of Worcester and of the Plateau of Central Massachusetts.

A SUMMARY.

Plateau of Central Massachusetts defined.

The eastern border of the plateau of Central Massachusetts is not clearly defined because of the long, gentle slope by which the highlands of the interior blend into the lowlands bordering the sea; but if the 500 foot level be assumed as the dividing line, we may trace an approximate border beginning in the south with the Blackstone river valley, thence northerly through the towns of Upton, Westboro and Northboro, crossing the head waters of the Assabet river near their sources, thence through Clinton, across the upper course of the Nashua river, and through Leominster, Lunenburg and Townsend. Westerly from this irregular line the plateau extends at an almost uniform level of 1000 or 1100 feet above sea level to the Wilbraham mountains and Pelham hills, which are the escarpment by which the land surface descends from the plateau to the broad lowlands of the Connecticut valley.

Rivers of the plateau.

This plateau is trenched easterly by the head waters of the Nashua river; southerly by the Blackstone, French and Quinebaug rivers; and westerly and southwesterly by the Millers, Ware, Swift and Quaboag rivers. These trenches are the pre-glacial river valleys, and are partially filled with the sands and gravels of the Glacial Period.

The plateau a peneplain.

This plateau is an ancient peneplain[1] whose general level is preserved in the hills of 1000–1100 feet elevation, with Wachusett, Little Wachusett, Watatic, Mt. Grace, Asnebumskit and a few other points, constituting Monadnocks, rising above the general level, and now serving as the points of radiation for the rivers of the plateau, just as they did for the rivers of this peneplain when it was at base-level.

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[1] Physical Geography of Southern New England, p. 276.—Wm. M. Davis.

Situation of Worcester in the plateau.

Worcester lies in the midst of this plateau, though somewhat near the eastern border, and is sunk about 500 feet below the plateau level. Here are found most of the rock systems which form this plateau, and under such conditions as to be specially favorable for study and the determination of their relations.

Worcester phyllite as related to the plateau.

Starting at Worcester, as a centre, we find first and uppermost the Worcester phyllite.[1] This rock underlies the central part of the city, and may be traced southwesterly and northeasterly across the state. It presents varying stages of metamorphism from a true argillite to a well defined mica schist; and contains, in different places, minerals resulting from metamorphism, as garnets, chiastolite, graphite, staurolite and anthracite. The laminae of the phyllite are frequently highly crumpled, producing folds almost infinitesimal in size and infinite in number. In some places these fine folds have been so compressed and flattened that they constitute the beginning of folia of a new structure across the old. In one place, also, this rock exhibits the development of a new structure by the rotation in sections of the laminae between fault planes.[2]

That the phyllite is really uppermost in position with reference to the other rocks of sedimentary origin found in Worcester is shown by its superposition in anticlines. In deciding as to its position in the geologic series, that is, its age, we rely on the specimens of Lepidodendron acuminatum found at the so-called coal mine here in Worcester; and we assign it to the Carboniferous. It probably belongs to an early part of that period.

On the east, this phyllite blends into a rusty, fibrolitic, graphitic mica schist which is found in small, detached patches within the Bolton gneiss area. These are probably remnants, indicating the former greater extension of this schist formation.

Carboniferous quartzite in the plateau.

The second and lower formation in Worcester is a micaceous quartzite[3] of a brownish grey color. This is associated with the phyllite in the latter's extent across the state, and occurs in bands east and west, sometimes also in the midst, of the phyllite.

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[1] Phyllite is used as defined by Merrill, Smithsonian Report, U. S. National Museum, 1890, p. 390. Also "Rocks, Rock-Weathering and Soils," p. 169. This phyllite is considered in detail in Chapter I.

[2] Explained on page 7. [3] Considered in detail in Chapter II.

Edge of the Plateau of Central Massachusetts from the East Side of Coes Pond. The Plateau Rises 500 Feet Above the Pond.

Because of the close relationship which these two formations bear to each other, the micaceous quartzite is also assigned to the Carboniferous period. They have been folded together on a large scale in the Oakdale-Millstone Hill anticline, the phyllite above and the quartzite beneath; and they have been crumpled together on a small scale in many places, as may be seen in the rocks of the deep cuts of the Boston and Albany and Boston and Maine railroads here in Worcester. These two formations appear, as far as can be seen in the midst of such severe folding, to be conformable.

Like the phyllite, the quartzite also shows the development of a new or secondary structure across the old or original structure; and in the case of the rock of Wigwam Hill the new structure was formed by the compression of small folds in the micaceous part of the quartzite, so that these compressed folds have become the folia of the schist as it is at the present time. This quartzite is in a few places conglomeratic, and the pebbles show deformation by pressure, being more or less flattened in the plane of the laminae.

Granite in the plateau.

Penetrating the Carboniferous phyllite and quartzite are granite bosses, of which Millstone Hill [1] is typical. These granites are later than the Carboniferous. That of Millstone Hill contains inclusions of both the phyllite and quartzite. The structure of the adjoining Carboniferous quartzite wraps around this granite, sometimes with the original bedding and sometimes across it. The rocks in the immediate vicinity of the granite have been greatly shattered, and now frequently appear as breccias, or made up of small angular blocks cemented together by fine quartz veins. Even the phyllite included in the granite is brecciated, indicating that the pressure was not excessive when this was included in the molten granite, hence that this granite did not solidify at a very great depth beneath the surface of the earth.

This granite of Millstone Hill contains orthoclase, generally white, with a triclinic feldspar, also white in color; quartz, generally smoky, but sometimes blue or amethystine; and a small amount of biotite. The quartz is distributed in somewhat coarse, granular particles outside of the feldspar, also in rounded grains, and rarely in small bi-pyramidal crystals, included in the

[1] Considered in detail in Chapter III.

feldspar. Fluorite also occurs in small particles as an original mineral in this granite. Beryl occurs in approximately spherical segregated masses, a foot or so in diameter, irregularly distributed through the mass of the granite. Other segregated masses also occur containing beryl, garnets, fluorite, molybdenite, sphalerite, pyrite and a light colored mica.

This granite boss is cut in various directions by aplite dikes varying in width up to twenty feet. A part of this aplite has been brecciated. The upcoming of this granite was probably associated with the folding of the phyllite and quartzite, as the boss is situated at the southern terminus of the Oakdale-Millstone Hill anticline. There are other granite areas distributed along this anticline.

Bolton gneiss in the plateau.

The Carboniferous quartzite, traced to the east, blends into a coarser grained, more highly metamorphosed quartzose mica schist, frequently containing alternating hornblendic bands. Between the laminae of this schist there has been forced, by parallel injection, much coarse granite. This schist and granite afford many minerals, both original and secondary, as enumerated in the study of the quarry near Quinsigamond. The alternation of schist and granite is very gneissoid in appearance, and often presents a close resemblance to a metamorphic conglomerate. From this appearance, and from the fact that it extends through the town of Bolton, and there contains the well known limestone mineral locality, this phase of the Carboniferous quartzite is called the Bolton gneiss.[1]

It is upon this Bolton gneiss that are spread the patches of the rusty, fibrolitic, graphitic mica schist phase of the Carboniferous phyllite already referred to as indicating the former greater extension of that formation.

Within this Bolton gneiss are also small areas of crystalline limestone in the towns of Boxboro, Bolton, Northboro, Millbury and Webster. These crystalline limestones abound in minerals formed during the metamorphism, and the Bolton and Boxboro limestones have long been noted for the scapolite and other minerals they afford.

Diorite in Bolton gneiss area.

Dikes of diorite[2] are found in the Bolton gneiss in the eastern part of Worcester and in Shrewsbury. This diorite, or these diorites are of interest as repre-

[1] Considered in detail in Chapters IV. and VI. [2] *Ibid.*, V. and VI.

Wilbraham Mountains, from Level Floor of the Connecticut Valley.

senting the basic cruptives in this study, and also on account of the minerals they afford, and the mineral transformations they present.

Extent of Bolton gneiss.

The Bolton gneiss may be traced northeasterly, easterly and southeasterly from Worcester and is found underlying Oxford, Millbury, Grafton, Shrewsbury, Northboro, Berlin, Bolton, Boxboro and other towns to the northeast. It is seen from this that the Bolton gneiss makes up a large portion of the eastern part of the plateau of Central Massachusetts.

Best direction in which to trace the rocks from Worcester.

If, in tracing the Bolton gneiss, we go east from Worcester on the Boston and Albany railroad, between North Grafton and Westboro, we pass from the gneiss on to a peculiar amphibolite. This latter rock belongs with the rocks of eastern Massachusetts rather than with those of the plateau, and does not help in our study, but rather confuses it, because this rock separates the Bolton gneiss along this line from the rocks of the eastern border of the plateau. It is well for us, therefore, in tracing the Bolton gneiss, to follow a southeasterly direction through the town of Millbury into the town of Sutton, and thus avoid the peculiar amphibolite, which does not reach southwesterly so far into the plateau region.

In this direction we find that the Bolton gneiss extends from Worcester through Millbury and the northwestern part of Sutton; then as we go still farther to the southwest, in the vicinity of West Sutton, we become aware that the rock beneath is quite different. This change from one formation to another may be nicely seen about three fourths of a mile southwest of West Sutton.

Westboro quartzite in the plateau.

This more ancient formation consists, generally, of a light colored, nearly white, finely grained, sugary quartzite which is, at times, actinolitic. It constitutes a comparatively narrow band extending through the towns of Webster, Oxford, Sutton, Grafton and Westboro; and is called the Westboro quartzite.[1] As it dips beneath the Bolton gneiss on the western side of a large anticline, the quartzite is considered older than the gneiss. In appearance this quartzite reminds one of the Cambrian quartzite of Western Massachusetts, though there is nothing in this eastern rock to definitely fix its geological age.

[1] Not before considered because not in Worcester.

Anticline making the southeastern border of the plateau.

The anticline, on whose western flank is this quartzite, is a broad one extending from Rhode Island into Massachusetts through the towns of Douglas and Uxbridge, Sutton and Northbridge, Grafton and Upton, Westboro and Southboro, to the road between Wessonville and Fayville in the last two towns, where it suddenly ends at a fault. This broad anticline pitches northeasterly. The rock of this anticline has been called the Northbridge gneiss.[1]

Northbridge gneiss in the plateau.

This Northbridge gneiss is of a light grey color, tinted flesh red by the feldspar. It is also of a medium coarse, granular texture, and of foliated structure. The feldspar and quartz in this gneiss are granulated. The indistinct foliation is apparently but the crushing and flattening out by pressure of quartz and feldspar particles into a plane at right angles to the direction of the crushing force. The biotite occurs in very thin, indistinct, bladed units, a half inch to an inch long and an eighth to a quarter of an inch wide; and each unit is made up of many little, black scales lying parallel to the foliation.

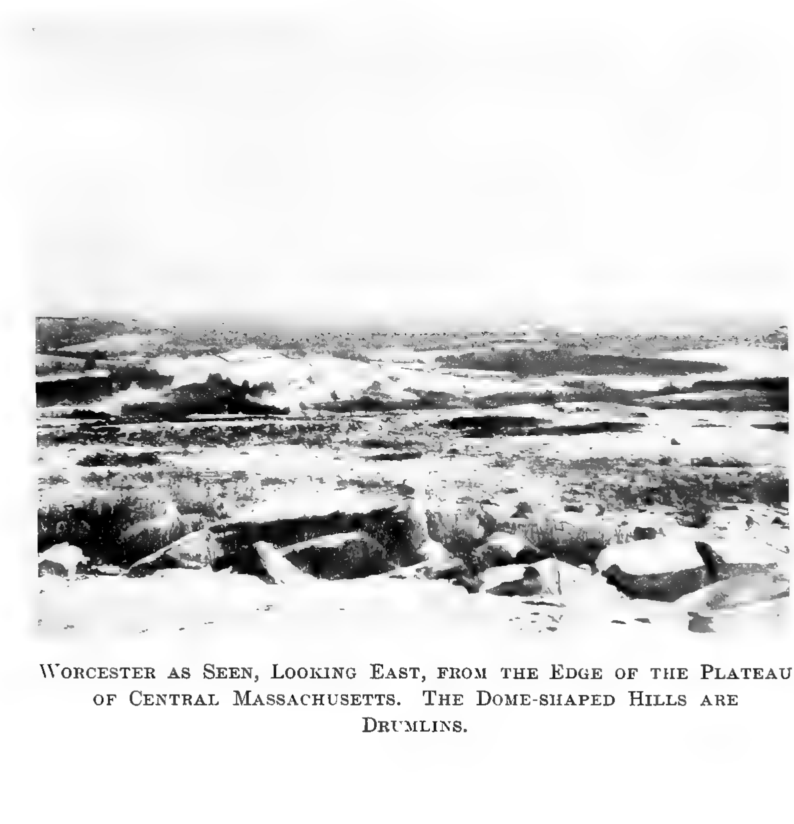
This Northbridge gneiss looks as if it was once porphyritic and massive, and had become granular and foliated through crushing. In some places we may find the uncrushed centres of the feldspar individuals, which are probably the remnants of the porphyritic crystals. Magnetite is always found in this rock, generally in fine irregular grains, sometimes as octahedra of considerable size.

This Northbridge gneiss, making up the anticline already described, and dipping easterly and westerly under the adjacent formations, is considered the most ancient of the rocks of the plateau of Central Massachusetts. This rock makes up the southeastern border of this plateau in the towns of Douglas, Uxbridge, Northbridge, Upton and Grafton.

Trace the rocks westerly from Worcester.

We have now briefly considered the rocks from Worcester to the eastern and southeastern border of the plateau of Central Massachusetts, bringing out the relation of each to the succeeding one, as far as we can; let us next start from Worcester, and, in like manner, trace the rocks westerly. Passing over the phyllite, which

[1] Not before considered because not in Worcester.



Worcester as Seen, Looking East, from the Edge of the Plateau of Central Massachusetts. The Dome-shaped Hills are Drumlins.

is found underlying the central part of Worcester, and which has already been considered, we find in the western part of the city the Carboniferous micaceous quartzite, identical with that found east, and in the midst, of the Carboniferous phyllite. This arrangement of these two formations is due to folding and subsequent erosion, by which the lower one is revealed alongside of the upper.

Paxton schist in the plateau.

On following this micaceous quartzite in the extreme western part of Worcester the rock becomes coarser in grain and abounds in parallelly injected granite, giving an appearance that frequently simulates a metamorphic conglomerate. This western and more highly metamorphosed phase of the Carboniferous quartzite has been called the Paxton schist,[1] from its occurrence in that town, just as the similar gneissoid extension of the same quartzite on the east is called the Bolton gneiss. The Paxton schist is less gneissoid than the Bolton gneiss because of a smaller proportion of injected granite.

Brimfield schist in the plateau.

Lying above the Paxton schist, as is shown by its upper position in an anticline in the northwestern part of Worcester, is a rusty, graphitic, fibrolitic mica schist[2] identical with the rusty, graphitic, fibrolitic mica schist found in patches within the area of the Bolton gneiss. This rusty schist has been crumpled into almost innumerable folds, both large and small, and contains much injected granite. Lying as it does above the Paxton schist, which is a more highly metamorphosed phase of the Carboniferous quartzite, this rusty schist bears the same relation to the Paxton schist that the Worcester phyllite bears to the Carboniferous quartzite; also on the east side of Worcester there is, in a small area, a transition from the phyllite into a like rusty, graphitic, fibrolitic schist; this rusty schist in the western part of Worcester, called the Brimfield schist, is, then, a more highly metamorphosed, or more coarsely crystallized, phase of the Worcester phyllite, and belongs to the Carboniferous period. This Brimfield schist, in addition to making up large areas, also occurs in limited patches within broad areas of the Paxton schist. These patches probably indicate the former extension of this upper Brimfield schist, and are remnants that have escaped in the profound erosion by which the rock sur-

[1] Considered in detail in Chapter VII. [2] *Ibid.*

face of this plateau has been formed. These two rocks, the Paxton and Brimfield schists, together with their included eruptives, make up the plateau of Central Massachusetts westerly from Worcester to the boundary as already defined.

Extension of the Carboniferous rocks.

But these Carboniferous rocks have even a greater extension to the south and north, and may be traced far into Connecticut on the one hand, and beyond the Massachusetts boundary into New Hampshire on the other. So far-reaching is the study on which we enter when we begin that of the rocks of Worcester. In the parlance of war, Worcester occupies the strategic point.

Time of formation of the plateau.

While, from what has been said, it may be seen that the plateau of Central Massachusetts is made up of Carboniferous rocks, the formation of this plateau, or of the peneplain which is the plateau surface, was much later, since the Juratrias rocks of the Connecticut valley were in their present position before this peneplain was formed by the rivers cutting this region down to base level, and the subsequent elevation of the land to the present altitude of the plateau. Being later than the Juratrias the formation of the peneplain has been assigned to the Cretaceous,[1] and the subsequent elevation, during which the rivers of the plateau cut the trenches which they now follow in this plateau, to the Tertiary.

Juratrias land surface of the plateau region.

But reaching farther back in geologic time than the plateau or the peneplain constituting the plateau surface, are the Monadnocks, Asnebumskit, Wachusett, Watatic, Mt. Grace, and others, rising in each case several hundred feet above the plateau level. These tell of another land surface, a thousand feet or so above the present plateau, very likely another peneplain and an earlier plateau. As the rocks in these elevations are the Carboniferous schists, or their included eruptives already spoken of, this more ancient land surface must have been made out of Carboniferous rocks, and hence must have been later than the Carboniferous period, and earlier than the Cretaceous. It may then be assigned to the Juratrias. The meaning of all this is that the Carboniferous rocks of the present time are but a part, perhaps a small part, of the original Carboniferous rocks; that these rocks extended to a con-

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[1] Wm. M. Davis, 18th Annual Rept. U. S. Geol. Survey, Part II., p. 14.

Mount Wachusett, Rising Nearly 1000 Feet Above the Surrounding Plateau.

siderable height above the tops of the Monadnocks, and that during the Juratrias period these rocks, including the eruptives, were profoundly eroded by the rivers, furnishing materials,—sands, clays, and pebbles,—which were deposited during that same period in the Connecticut valley region, which was then an arm of the sea, and in other regions whither the rivers carried them.

Such, in brief, is the study of the rocks of the plateau of Central Massachusetts, sunk in which is the broad Tertiary valley in which Worcester is situated.

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